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Optimization of Biological Recycling of Plant Nutrients in Livestock Waste by Utilizing Waste Heat from Cooling Water

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Optimization of Biological Recycling of Plant Nutrients in Livestock Waste by Utilizing Waste Heat from Cooling Water

by

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16. ABSTRACT

The report summarizes a 5-year study of the beneficial uses of waste heat from condenser cooling water from steam-electric generating plants. The major effort addressed the recovery of plant nutrients in swine manure by aquatic farming of selected fish and Chinese waterchestnuts. Another effort included biogas production from swine manure in an anaerobic digester and the use of the digester waste to fertilize the aquatic farming system. Optimum recovery of plant nutrients resulted from operation of an integrated fish and waterchestnut system. Flowing water systems were 30-50% more productive than static systems. Annual fish yields of 5000-7000 lb/acre are projected for a properly stocked system over a 150-180 day growing period. Similarly, waterchestnut yields of nearly 17.8 tons/acre and dry hay yields of 6.7 tons/acre from sand-bed filters would be expected when fed wastewater from the fish system. The quality of the water leaving the sand beds would meet tertiary wastewater treatment standards during the growing season. An estimated 2000-head swine facility with a $400,000 investment would annually produce a 20% rate of return, save 360,000 bbl of oil through waste heat utilization, and produce biogas equivalent to 3000 bbl of oil.

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Waste Treatment	Gases	Biogas	07D
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ABSTRACT

This report presents results from a 5 year study to develop aquatic methods which beneficially use condenser cooling water from electric generating power plants. A method is proposed which uses a system for aquatic farming. Livestock waste is used to fertilize planktonic algae production and filter-feeding fish are used to "biologically harvest" the algae, condenser cooling water (simulated) is used to add "waste heat" to the system, and emergent aquatic plants are used in a flow through series as a bio-filter to improve the water quality and produce an acceptable discharge.

Two modes of operation were tested; one uses untreated swine manure as the source of aquatic fertilizer and the other uses anaerobic digester waste as a means of pretreating the manure to produce an organic fertilizer.

A set of operating conditions (temperature, retention time, fish stocking rate, fertilizer rates, land and water requirements, suggested fish and plant species, and facility design) were developed from these results. The integrated system allows continual use of power plant condenser cooling water from plants in the southeastern United States.

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CONTENTS

Page

Disclaimer ii
Abstract iii
Figures vii
Tables ix
Abbreviations and Symbols xii

I. Introduction 1
II. Summary and Conclusions 2
III. Recommendations 5
IV. Integrated Concept 7
    A. Background 7
    B. Livestock Waste 9
    C. Condenser Cooling Water 10
    D. Algae 11
    E. Fish 16
    F. Water Polishing 18
    G. Water Quality 22
V. Production Test 27
    A. Algae 28
    B. Fish 37
        1. Culture Selection 37
        2. Fertilization Techniques 41
        3. Fertilization and Stocking Interaction 47
        4. Water Management (Static vs Flow Through) 47
    C. Plants 51
        1. Plant Selection 53
        2. Water Chestnut Culture 53
VI. Pilot Demonstrations 62
    A. Swine Waste Test 62
        1. Facilities 62
        2. Fish Production 68
        3. Water Chestnut Production 71
    B. Anaerobic Digester Test 73
        1. Facilities 73
        2. Digester Performance 75
        3. Fish Production 78
        4. Duckweed Production 81
        5. Water Chestnut Production 81

CONTENTS (continued)

Page

VII. Water Quality 83
A. Production Test Periods 83
B. Pilot Demonstration 89
1. Swine Waste Test 89
2. Anaerobic Digester Waste Test 91
VIII. Economic Analysis of a Power Plant Aquafarm 94
IX. References 102
X. Appendix 115

FIGURES

Number Page

1 Components of the integrated concept for optimizing the recovery of plant nutrients in livestock waste by utilizing waste-heated water 8

2 Growth of algae cultures and disappearance of NH_3-N at two temperature ranges. 25-30°C = X, 15-20°C = ⊗, NH_3-N = ———, and dry weight = ------, @ 40-cm depth during September 1976 29

3 Influence of temperature on suspended soilds concentration during cloudy and clear weather in the winter period (November 1977) 32

4 Algae growth (cells/mℓ) as a function of temperature and time during the "start-up" phase of algae cultures (November 1977) 33

5 The observed morning dissolved oxygen content in growing algae cultures as a function of temperature and time during periods of cloudy and/or clear weather 34

6 The change in total NH_3-N in algae cultures 24 hours after manure addition as a function of time and temperature 36

7 Comparison of the relative weight gain (net gain/initial weight x 100) of silver carp, bighead carp, and tilapia cultured together for 52 days in swine-manure-enriched pools or fed algae slurries grown with swine manure (August-September 1977) 46

8 Relationship between organic fertilization rate and fish production as influenced by fish population and water management 48

9 Relationship between organic fertilization rate and fish production as a function of fish stocking rate (1977-1979) 50

FIGURES (continued)

Number Page

10 Experimental design for the flowing water production test during the 1978 season (May 23-October 25, 1978) 56

11 Fish growth during the spring/summer period using swine manure in the pilot demonstration (March 1-August 27, 1979) 69

12 Average monthly water temperatures in the pilot demonstration using swine manure during the spring/summer/fall season (March 1-October 31, 1979) 72

13 Fish growth rates in the pilot demonstration using anaerobic digester waste as the source of fertilizer (November 14, 1979-September 4, 1980) 79

14 Chronological order of culture events in fish tanks and water chestnut sand filtration beds for flow rate production test during the 1979-1980 season 84

15 Chronological order of culture periods in the pilot demonstrations using swine manure and anaerobic digester liquid waste 85

TABLES

Number		Page
1	Composition of Scenedesmus and Spirulina compared to soybean meal	15
2	Standing crop, productivity, and yield data for four species of aquatic vascular plants	19
3	Effect of water hyacinth and alligator weed on certain water quality characteristics	20
4	Comparison of mean values of selected water quality parameters in the terminal unit of a six-unit lagoon wastewater treatment facility at Quail Creek, Oklahoma	25
5	Effect of manure dilution on ammonia, suspended solids, and algae growth	30
6	Effect of temperature on suspended solids at threshold levels of manure dilution	31
7	Elemental analysis of algae grown at three temperatures on swine manure	37
8	Phytoplankton observed in swine manure cultures from 1975-1978	38
9	Species abundance observed in algae cultures collected in June 1977 from greenhouse-grown cultures and open tank cultures fertilized with swine manure	39
10	Crude protein content of suspended solids of selected cultures of algae	39
11	Fish production data 1976-1979	42
12	Silver carp growth in 1976 pool study (July-September 1976, 72 days	45
13	Net production of three species of fish cultured together in swine-manure-enriched pools (August-September 1977 yield trials, Muscle Shoals, Alabama)	42

TABLES (continued)

Number		Page
14	Standing crop and total net production of silver carp and tilapia cultured together for 109 days (1978) in static water receiving swine manure as an organic fertilizer	49
15	Standing crop and total net production of silver carp and tilapia cultured together for 109 days in static and flowing water systems	52
16	Effect of manure and commercial fertilizer application on Chinese water chestnut yield	55
17	Recovery of N and P in Chinese water chestnut plant fractions - 1978	58
18	Partial budget for N and P in flow-through system - 1978 (147 days into the 1978 test [kg/147 day-ha])	59
19	Comparison of effluent from sand filtration beds with and without water chestnuts	60
20	Yields of water chestnuts and hay in response to daily irrigation with fish waste water (1979, Colbert County, Alabama)	60
21	Ratio of fish to water chestnut area tested in 1978 and 1979	61
22	Browns Ferry Nuclear Plant monthly average condenser discharge temperatures	64
23	Stocking and harvest data for five species of fish cultured together for 119 days (10-26-78 to 2-22-79) in a 0.04-ha (0.1-Ac) cooling lagoon receiving the total waste of eight market hogs	65
24	Stocking and harvest data for five species of fish cultured together for 180 days (3-1-79 to 8-27-79) in a 0.04-ha (0.1-Ac) cooling lagoon receiving the total waste of eight market hogs	66
25	Stocking and harvest data for five species of fish cultured together for 33 days (9-9-79 to 10-12-79) in a 0.04-ha (0.01-Ac) cooling lagoon receiving the total wastes of eight market hogs	67
26	Chemical and physical characteristics of the waste streams associated with the anaerobic digester	76

TABLES (continued)

Number Page

27 Seasonal averages of effluent water quality from production test with fish and water chestnuts (1979) . . 86

28 Seasonal averages of effluent water quality from production test with fish and water chestnuts (1980) . . 88

29 Effluent water quality from swine waste fertilized pilot demonstration test (May-October, 1979) and water source used in the test 90

30 Effluent water quality from anaerobic digester pilot demonstration (January-April, 1980). 92

31 Major assumptions of investment analysis of a theoretical livestock-aquafarm system using power plant condenser cooling water. 96

32 Fixed costs, variable costs, and revenue items used in investment analysis of a theoretical livestock-aquafarm system using power plant condenser cooling water 97

33 Inflation indices utilized in computerized investment analysis of a theoretical livestock-aquafarm system using power plant CCW. 100

34 Results of investment analysis of hypothetical biorecycling enterprise 101

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BOD -- biological oxygen demand
COD -- chemical oxygen demand
SS -- suspended solids
TS -- total solids
VS -- volatile solids
TVS -- total volatile solids
STS -- settled solids
TKN -- total Kjeldahl nitrogen
ORGN-N -- organic nitrogen
TOTP -- total phosphorus
TOC -- total organic carbon
TOTC -- total carbon
TC -- total coliforms
FC -- fecal coliforms
DO -- dissolved oxygen
DOB -- dissolved oxygen in plant beds
DOP -- dissolved oxygen in plant effluent
HARD -- hardness of water
TA -- total alkalinity
PA -- phenolphthalein alkalinity
CB -- conductivity fish effluent
CP -- conductivity plant effluent
CCW -- condenser cooling water

SYMBOLS

Ac -- acre
As -- arsenic
Ca -- calcium
Cu -- copper
K -- potassium
Fe -- iron
Mg -- magnesium
Mn -- manganese
Na -- sodium
NH_3 -- ammonia
NH_4^+ -- ammonium
NO_3-N -- nitrate nitrogen
NO_2-N -- nitrite nitrogen
P -- phosphorus
Pb -- lead
Se -- selenium
T -- temperature
°C -- centigrade
°F -- fahrenheit
Zn -- zinc
ℓ -- liter
mℓ -- milliliter
kg -- kilogram
ha -- hectare
g -- gram
lb -- pounds
m -- meter
ft -- foot
gal -- gallon

SECTION I

INTRODUCTION

This report summarizes a 5-year TVA study conducted to determine how the condenser cooling water from electric power plants can be used benefically in an aquafarming approach. Recovery of plant nutrients contained in livestock manure by aquatic farming comprised a major effort in these studies. Warm water simulating condenser cooling water temperatures was used to determine its additive effects on the aquatic systems.

Schemes to recycle and recover plant nutrients from wastewater sources are numerous and were summarized in a recent review (Maddox et al., 1978). Confined livestock production; growing populations; and higher costs of energy, fuels, and fertilizer have increased public awareness of environmental pollution and resource conservation.

Wastewater aquaculture using waste-heated water and/or livestock manures is a relatively new concept in the United States. However, wastewater approaches to aquafarming have been practiced for centuries in Old World countries. Such approaches increase the useful productivity of the water, while recovering the valuable nutrients and decreasing pollution. The additional production provides an opportunity to improve the economics and the efficiency of the production enterprise which produces the waste streams.

This study has focused on developing an approach which could accomplish these objectives. The approach is not limited to the chosen livestock, source of waste water, plant and animal species, geographic location, or the self-imposed water quality standards. The proposed integrated approach allows the flexibility needed to adapt the system to specific sites and for certain needs in keeping with its role for resource recovery and energy conservation.

SECTION II

SUMMARY AND CONCLUSIONS

This study has resulted in the development of an integrated system which will use power plant condenser cooling water to permit production of fish and water chestnuts and, at the same time, produce a sufficiently clean waste effluent for discharge to the environment. The system uses flowing water for continuous application of waste heat and organic fertilizers to produce aquatic animals and plants on an annual basis.

The fish and water chestnut system should be operated as an integrated system for optimum recovery of plant nutrients from organic fertilizers such as swine waste. Flowing water systems have been found to be 30 to 50% more productive than static water systems. The swine manure is flushed directly into the fish and algae culture ponds with virtually no odor problems evident because sufficient oxygen is maintained by the growing algae.

The loading rates of manure must be maintained at a specified level to assure proper oxygen levels for growing and maintaining fish. The flowing water system should maintain a waterflow sufficient to replace all fish water in 10 days. This flow rate is equivalent to 655 ℓ/ha (70 gal/Ac) per minute continuously. The waste from 5,000 kg of pigs should be applied to a hectare 91 cm deep (11,000 lb/Ac @ 3 ft depth). This amount of manure will stimulate a lush growth of algae which will provide the feed for filter-feeding fish.

Fish (such as tilapia, silver carp, bighead carp, and bait minnows) can be grown in this type system. Each offer different advantages and can be grown separately or together (polyculture). Tilapia appear to be easily marketed as a fresh food, while the carp species may require food processing for large-scale marketing. Fingerling supplies suitable for stocking are not readily available but can be purchased from selected vendors. State laws should be consulted before interstate transport of exotic species is considered.

Tilapia cannot survive water temperatures below 13°C (55°F) but may be overwintered in power plant water with raceway facilities. Fish (tilapia) should be stocked into the aquatic farming system at a density equivalent to 10,000 to 15,000/ha (3,240 to 4,080/Ac) with fish weighing approximately 30 to 60 g (1-2 oz) each. Accessory species, such as silver carp and bighead carp, can be stocked at a rate equivalent to 2,500/ha (1,000/Ac). Silver carp can be substituted for tilapia in this stocking ratio if they are the principal fish grown in the system, and bighead can be stocked up to 25% of the total population. Annual fish yields of 5,600 to 7,850 kg/ha (5,000 to 7,000 lb/Ac) can be expected from this system if proper size fish are stocked and grown for 150 to 180 days.

The fish waste water should be irrigated onto a sand-bed filter growing Chinese water chestnuts with an area equal to approximately one-half the water surface area of the fish system (1:2 ratio). Chinese water chestnuts should be planted on 51-cm (20-in.) spacings early in the spring and the bed maintained flooded 5 to 10 cm deep (2-4 in.). Plant tops (shoots) can be cut and baled for hay after the first frost. The water chestnuts can be harvested with modified root harvesting equipment from the dry fields. Yields of 15 metric tons/ha (6.7 tons/Ac) of dry hay and nearly 40 metric tons/ha (17.8 tons/Ac) of water chestnuts can be expected. Harvestability of the hay and chestnuts is highly dependent on water management but may approach 80%.

The water chestnut hay is suitable for cattle feed and the water chestnuts can be sold for gourmet cooking. Additionally, the water chestnut is a sugar and starch crop suitable for animal feed or use as a possible source of carbohydrates for alcohol fermentation.

Anaerobic digester waste has been preliminarily tested and found to be suitable as an aquatic fertilizer. The application of nitrogen to the system may be two times as high due to the treatment and conversion of a large percentage of organic nitrogen into ammonia. Reduced oxygen demand of the waste as a result of the pretreatment process permits higher waste loading to the aquatic system and reduces the land area required to recover and treat a given amount of swine waste. The swine animal weight required to achieve comparable results in the fish system is approximately one and one-half times the raw waste recommendation (18,450 kg/ha [16,500 lb/Ac]). The fish:water chestnut area ratio should approximate 1:1 instead of 2:1 as recommended when using diluted and untreated swine waste as the fertilizer. Therefore, the production of water chestnuts would increase in proportion to the increased planting area using anaerobic digester waste in the same type of system.

Water quality standards equal to tertiary wastewater treatment standards can be achieved with this system during the spring/summer/fall growing season. Fish and crop rotation with tilapia to silver carp and Chinese water chestnut to duckweed species during the winter season can produce water quality equivalent to secondary wastewater treatment standards during the winter season. Water losses due to evaporation and seepage can be high if special care is not taken to reduce ground infiltration losses. Water losses of 10 to 20% can be reasonably anticipated with these systems. However, evapo-transpirational heat losses are high and the water is completely cooled in the process. Selective uptake of plant macro- and micronutrients from the water effectively prevents any appreciable change in the water hardness and alkalinity through the system. Fecal coliform counts are greatly improved in the effluent relative to the water source during the growing season. Fecal coliform counts were unchanged in the effluent relative to the water source in unheated tests during the winter, but were higher in simulated waste-heated tests during the winter.

Economic analysis of a hypothetical 2,000-head swine facility indicated an investment of about $390,000 would be required. This investment could generate $685,000 gross revenue per year and produce a 20% rate of return on the waste nutrient recovery investment. It would require 18.2 ha (45 Ac) of land, use 2,000 gal/min of waste-heated water, save the equivalent of 360,000 barrels of oil, produce the equivalent of 3,000 barrels of oil as fuel gas (biogas), and provide the equivalent of about 10 jobs in the community. The potential exists for much larger facilities at power plants, and much potential exists for similar technology on farms. Additionally, this technology can be applied in separate components (fish, aquatic plants, livestock, anaerobic digester, and water polishing) to accomplish site-specific tasks. Cooling lagoons for power plants can be made compatible with aquatic farming practices to accomplish both energy recovery and conservation of natural resources.

SECTION III

RECOMMENDATIONS

A water pricing policy and reliability of the condenser cooling water (CCW) needs to be established for commercial ventures. Cost effectiveness studies need to be conducted with actual power plant facilities. Although much effort has been put into developing beneficial uses of CCW in the U.S., to date few commercial demonstrations have successfully demonstrated the beneficial uses of this form of waste-heated water.

A national policy on the environmental requirements for power plant cooling water and water chemistry should be developed which would stimulate the beneficial uses of significant amounts of water and waste heat in CCW. Aquafarming lagoons can be made compatible with power plant needs for cooling capacity. However, reliability of cooling capacity for the power plant should not be sacrificed because of seasonal changes for needed heat in the use facility. Conversely, reliability of needed heat and/or water should not be sacrificed at the expense of the commercial production which uses the waste heat. Clearly, a compromise must be accomplished between cooling needs of a power plant and reliability of waste-heated water.

Cooling ponds should be used to accomplish the cooling function of power plants when possible. Aquatic farming with filter-feeding fish and harvestable aquatic plants should be developed as a mutual solution for the cooling needs and beneficial use of the CCW. These systems are very dependent on proper management to take advantage of the seasonal changes in sunlight and water temperatures. Biologically rate-limiting processes require sufficient time to accomplish the cooling capacity needed for power plants, and the economics require maximizing the return on given investment of time, land, and capital.

Wastewater regulations should be reevaluated and restructured to permit the use of these systems without jeopardizing public health and safety. Closed-cycle power plants need sufficient water to maintain dilution water for blowdown and for injecting smaller waste streams into the blowdown water for environmental discharge and dilution. Power plant operational designs and permissible discharge regulations should be structured to permit and promote compatible uses of this type of water discharge for aquatic farming technology.

Additional work is needed to explore other crops and management schemes to improve aquafarm production during the winter. The choice of plants and animals for winter growth is important enough to warrant additional research and development. More compatible crop rotations between summer and winter seasons need to be developed to ensure a more even use of CCW throughout the year.

The principles of wastewater aquafarming can be used with other wastewater sources. Future work should investigate the use of organic wastewater farming with other livestock, municipal sanitary waste water, and/or industrial organic waste and waste water. Studies with such wastewater sources should result in a definite recommendation for operational conditions.

Anaerobic digester waste and digester operation needs further study as an integrated approach to aquafarming and wastewater management. Pretreatment of organic waste can serve to reduce the health hazards and improve the economics of the aquafarming system and the fuel biogas system. Research has not provided sufficient technology to economically justify the expense of only producing fuel credits for these systems, yet some systems can effectively produce biogas fuel to meet site-specific needs for fuel and waste treatment.

Regulatory constraints should not limit the use of exotic species of plants and animals. Many kinds of plants and animals have been identified and developed for our agricultural production. Future crops may be identified which permit the use of aquatic production practices. Innovative production systems should demonstrate advantages which outweigh the disadvantages to the ecology. Many States have laws against the use of exotic species for reasons which speculate on the possible damage to site-specific ecological situations.

SECTION IV

INTEGRATED CONCEPT

The integrated concept studied and developed in this report has six basic components. They are: (1) livestock waste, (2) condenser cooling water, (3) algae production, (4) fish production, (5) water polishing, and (6) effluent water quality. These components are graphically depicted in Figure 1. The methods of integrating the components in this study represent a modification of the phytoplanktivorous system. They have been studied individually by the authors and others prior to their selection and integration into a pilot demonstration to determine the holistic effect on the resource enterprise.

BACKGROUND

The initial approach taken by this research program was presented by Williams in 1971 (Williams, 1971). The need to recover and recycle plant nutrients was recognized because of the increasing cost of fertilizer, trends toward confined livestock facilities, and interest in water pollution abatement. During the 1970's, TVA launched a heavy commitment to generate electricity with nuclear power and to assess the potential impact of waste-heat discharges into the Tennessee Valley streams. Waste-heated water was seen as a possible management tool to utilize the resources in the two wastewater streams generated in the Tennessee Valley (condenser cooling water and confined livestock waste water).

Aquacultural approaches to the integrated use of these two waste streams offer potential for the mutual resource recovery effort. Useful productivity of either of these waste streams is low without the proper management and technological approach to alter their physical and chemical characteristics.

A literature search (Stanley, 1974) was conducted to ascertain the state-of-the-art for livestock waste recycling and to identify the potential benefits. This study concluded that three systems offered potential and warranted further investigations. The three systems of aquatic bio-recycling initially proposed were (1) duckweed consumed by grass carp; (2) algae consumed by a freshwater shellfish, e.g. Asiatic clams; and (3) algae consumed by a phytoplanktivorous fish, e.g. silver amur. The end product of these aquatic approaches (grass carp, Asiatic clam, or silver amur) would be used as livestock feed or as a protein feed supplement.

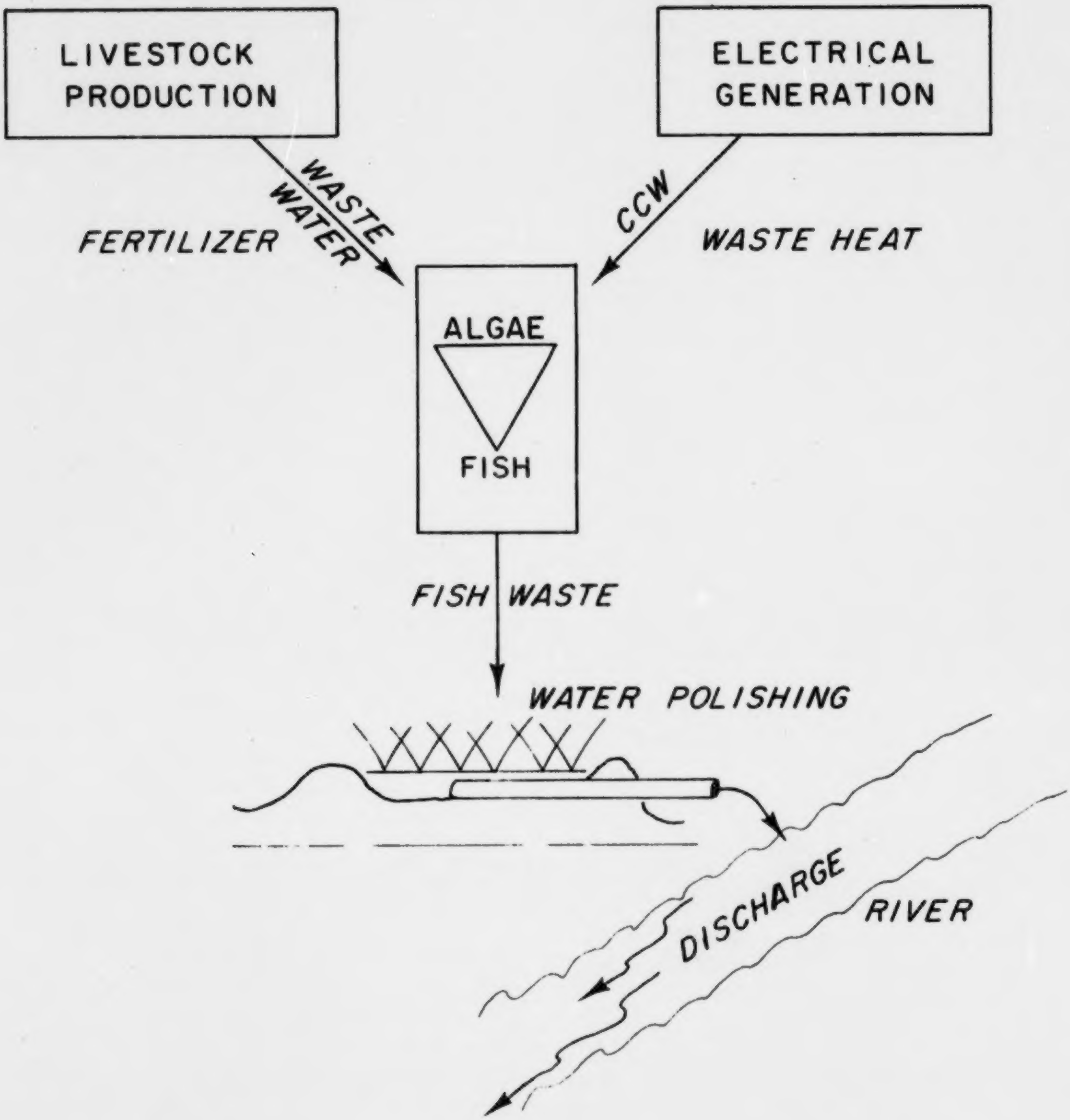

Figure 1. Components of the integrated concept for optimizing the recovery of plant nutrients in livestock waste by utilizing waste-heated water.

Asiatic clams (Corbicula spp.) occur abundantly in the Tennessee River and its tributaries. This clam has become a major pest in power plant intake water. It blocks intake screens, fouls condenser tubes, and produces major problems in power plant management. Low meat to shell ratio, difficulties in shucking, and its natural abundance are potential constraints to commercial production of the Asiatic clam. One potential use is a source of calcium and protein for poultry layer rations. Because of these problems and the lack of available culture information, this approach was not developed.

The duckweed-grass carp system could offer some potential for resource recovery of waste heat and organic fertilizer. However, the use of grass carp was and remains illegal in many of the Valley States. Much of the controversy stems from the possible adverse influence of the grass carp (Ctenopharyngodon idella) on native aquatic plants and on the habitats of wildlife populations. This approach has not been technically developed and appears to offer little potential in the Tennessee Valley.

The third alternative is to use phytoplanktivorous fish. This appears to have the best potential for acceptability and flexibility for widespread application. The specific components of such a system were evaluated, refined, and expanded to develop an integrated system that could be implemented.

LIVESTOCK WASTE

Swine production was selected for this approach. Swine production is second only to poultry in terms of animal numbers in the Valley States. Poultry is the most abundant confined livestock. Swine waste is the third most abundant source of available livestock manures. Dairy waste and broiler house waste are estimated to be larger in quantity. Considering the waste characteristics and production management, swine manure could be the most easily adapted form to the integrated approach. Livestock production systems which have automated and/or daily removal of waste, high fertilizer strength, and predictable quantities and quality would offer the best potential for the integrated approach.

Broiler production does not use automated daily removal processes to remove poultry waste from the production facility. Additionally, broiler litter waste has been shown to have a high value as a source of nonprotein nitrogen for ruminant animals.

Dairy waste is diluted by large volumes of washing water for cleaning and disinfecting purposes. The waste streams vary in volume and strength depending on management practice. Dairy systems must be supported by large forage production areas for winter feeding and summer grazing. Such livestock systems may not be compatible with land availability at a power plant.

Swine production uses a variety of facility designs, waste removal methods, waste stabilization methods, and management approaches that could be adapted to the integrated system. Swine facilities are commonly designed for complete confinement, environmental control, water flushing methods, aerobic and anaerobic waste stabilization, and management approaches that result in complete dependence upon nutritionally balanced commercial feed rations.

CONDENSER COOLING WATER

Power plant condenser cooling water (CCW) can vary in volume, temperature, chemistry, and availability. All of these factors can significantly influence the reliability and performance of any system that attempts to use the power plant CCW in a beneficial manner. A system which derives a principal benefit from CCW could be developed for any one or combination of CCW properties or combinations of these CCW properties. Examples of these uses would be irrigation for crop production, space heating for comfort or greenhouse production, and as a source of wash water in the food processing industry which requires certain minimum standards in water chemistry.

The availability of CCW directly or indirectly affects all proposed beneficial uses that could be derived from CCW. Availability is mainly a function of power plant design, location, and management. Beneficial uses of waste-heated water should not be unduly constrained by its availability or the application of such systems will be subject to a high degree of technical and economic risk.

The integrated approach of aquafarming has the potential to use CCW directly as a growing medium, as well as benefit from its heat content and improve its water chemistry. The rate-limiting process is the rate at which water quality can be improved and remain compatible with the aquafarming approach. Therefore, heat transfer effectiveness of CCW is of secondary importance in this approach. This reduced dependency upon reliable water temperatures can serve to lessen the technical and economic risk associated with commercial ventures. The choice of various species of livestock, fish, and aquatic plants can place a greater or lesser dependency upon reliable water temperatures. Tropical species of plants and animals could place a high dependency upon the waste heat content of CCW. If the CCW proves to be a reliable source of heated water and a high dependency has been designed into the system, then large benefits can be derived from the commercial use of power plant CCW.

The flexibility of this integrated system should increase the acceptance of this approach and be reflected in the choice of plant and animal species. The CCW can be completely cooled by this system to remove all of the waste heat content. Such approaches to beneficial uses of CCW require relatively larger land areas than other systems. However, systems that result in large cooling capacities can be more efficient in heat removal in terms of energy removed per unit of land area and can result in a more predictable and reliable cooling capability.

ALGAE

Algae populations are the basis of this integrated approach. The microscopic free-floating plant life (phytoplankton) and animal life (zooplankton) serve as the principal food source for phytoplanktivorous fish. Bacteria biologically convert the potential fertilizer constituents into a reusable form for plants. This synergistic relationship between bacteria and plankton is required to maintain a "balanced" system which uses the organic fertilizer to the advantage of useful and harvestable production. The major effect of waste heat is to raise the temperature and increase the respiration rates of bacteria and algae. This temperature effect increases the production of CO_2 from organic substrates by the microbial population. This CO_2 is available for algal photosynthetic fixation of carbon in periods of adequate sunlight. Photoperiod and sunlight intensity are both important for algal growth.

The temperature influences on the respiration rate of this system is beyond the scope of this review. The reader is referred to the following references for background: Boersma et al., 1974; Dunstan and Tenore, 1972; Fogg, 1975; Goldman, 1977; Goldman and Carpenter, 1974; Goldman and Ryther, 1976; Hoogenhout and Amesz, 1965; Jorgensen, 1968; Oswald and Golueke, 1968a; Oswald and Golueke, 1968b; and Sorokin, 1971. The following discussions are limited to influences on algae physiology.

Optimum temperatures for most algae are between 20° and 25°C (68° to 77°F), but thermophilic strains of Chlorella and Anacystis grow best at about 40°C (104°F). Temperature optima for biomass production can vary with light intensity and concentration of certain culture nutrients, and adaptation to different temperatures does occur in algal cultures (Fogg, 1975).

Temperature was found to exert an insignificant influence on biomass concentration when five marine algal species were tested over a range of temperatures from 10° to 30°C (50° to 86°F) (Ryther, 1976). However, temperature does have a large effect on species dominance. This effect is influential in making species control in open-air large cultures difficult if temperatures fluctuate significantly over short periods of time, but could help provide the necessary control to maintain relatively monotypic algal species in the system.

Chemical composition and cell physiology of phytoplankton are influenced by temperature. Optimum temperature for cell division and for nutrient uptake has been shown to be different for some algal species (Goldman, 1977). Therefore, system designs to optimize biomass production with temperature may not be optimum for nutrient uptake rates, resulting in a product with lower nutritional quality for filter-feeding organisms, e.g. fish. If nutritional quality is lost, theoretical maximum yields of biomass from a wastewater aquaculture system have little meaning when considering total efficacy. Light quality, intensity, and photoperiod may well be the most important climatic factors in controlling biomass and standing crops of algae. Adaptation to light intensity occurs over a wide range of light intensities, and photosynthetic efficiency generally ranges between 1% and 5% for waste-grown algae (Boresma, 1974). Most algal species are lightsaturated at low sunlight intensities of approximately 538.2 lux (500 ft candles). A wide range of production rates is reported and generally falls between 1 to 50 g/m^2 (0.0002 to 0.01 lb/ft^2) per day of dry-weight algal matter.

Scenedesmus spp. have been reported to reach 28 g/m^2 (0.0057 lb/ft^2) per day in Rupite, Bulgaria (Stengel, 1976), with yearly averages of 10 to 12 g/m^2 (0.0020 to 0.0024 lb/ft^2) per day. Others have measured growth of 20 g/m^2 (0.004 lb/ft^2) per day at 1,800 $kcal/m^2$ (663 Btu/ft^2) per day of sunlight (Wesselins, 1973), 33 g/m^2 (0.0067 lb/ft^2) per day at 4,300 $kcal/m^2$ (585 Btu/ft^2) per day (Kok, 1954). These results compare favorably with yields of 17 to 28 g/m^2 (0.003 to 0.006 lb/ft^2) per day which were recorded in this study. Dry-weight yields are reported to range between 45 metric tons/ha (20 tons/Ac) to 90 to 112 metric tons/ha (40 to 50 tons/Ac) per year (Golueke, 1977).

Cultures exhibit an optimum depth due to light penetration in turbid waters. These depths for culture growth are dependent upon the physical characteristics of the waste water and standing crop of algae-bacteria biomass at a given level of irradiance. Generally, the optimum depths fall between 5 to 20 cm (2 to 8 in.) in temperate regions, but greater depths are possible if cultures are agitated continuously, intermittently, or if agitated vigorously once a day (Oswald, 1968). At stirring speeds of 30 to 60 cm/sec (1 to 2 ft/sec), depths of 30 to 35 cm (12 to 14 in.) are possible with little loss of photosynthetic efficiency in thick cultures of waste-grown algae.

Photosynthesis of the algal cultures and the form of nitrogen available for assimilation (ammonium, ammonia, nitrite, nitrate, urea, or organic nitrogen) affect the alkalinity and pH in a complex manner (Brewer and Goldman, 1976). Generally, pH in an actively growing wastewater algal culture ranges between 8 to 10, but a pH of 11 is possible. CO_2 is usually preferred over bicarbonate as a carbon source. High pH values improve the efficiency of CO_2 utilization (Soeder, 1976). CO_2 injection reduces the pH approximately 1 or 2 pH units, but it has generally been dismissed as economically unsound to apply CO_2 in large-scale cultures. However, availability of a large supply of cheap CO_2, such as found in some geological formations, coal gasification projects, and scrubbed stack gases could change this situation in certain locations.

Ammonia (NH_3) stripping is greater at high pH values (pH > 8.2) and significant nitrogen losses can occur under these conditions, especially if mechanical aeration is used. Ammonia at concentrations of 24 ppm-N as NH_3 and pH > 8 inhibited photosynthesis and growth of Scenedesmus obliqus, Chlorella pyrenoidosa, Anacystis nidulans, and Plectonema boyanum in high-rate oxidation ponds (Abeliovich, 1976).

Forsberg (1976) has reported that plant nutrients associated with pollution and eutrophication are the same as those needed to increase productivity. Municipal sewage generally ranges between 25 to 45 ppm total nitrogen and 8 to 15 ppm phosphorus. The nitrogen form in raw sewage is usually ammonium and organic nitrogen and in secondary treated effluent, nitrate-nitrogen. Livestock manures can range upward to 10,000 ppm total nitrogen with nearly one-half as ammonium nitrogen if storage is practiced in the slurry form.

Nitrogen:phosphorus (N:P) ratios are important if most of the phosphorus is to be removed as cellular P. The N:P ratios of 2:1 to 4:1, commonly found in sewage (Forsberg, 1976), contain too little N or excess P for phytoplankton needs when diluted to proper concentrations for cultures. Ratios of N:P of about 16:1 are desirable if biological wastewater treatment is used to remove P. Nitrogen is present in livestock waste in large quantities, but phosphorus removal may be necessary to obtain desired N:P ratios and accomplish wastewater treatment. Phosphorus can be reduced by maintaining high pH (pH > 9) and precipitating insoluble inorganic phosphorus.

Water standards for discharge into a navigable waterway can usually be met if sufficient nutrients and suspended solids can be removed from the livestock waste-grown algal slurries. Chemical oxygen demand (COD) in algal cultures generally shows a linear relationship with algal concentration, and 1.19 mg of O_2/mg algae is required for complete oxidation. Degradation of supernatant COD may require 90 days (Friedman et al., 1975).

Those organisms capable of removing attached or planktonic algae have the effect of stabilizing the algal community. In nature, a balance of these feeders causes nonselective feeding on the phytoplankton community. Production of algae for filter-feeding organisms establishes an artificial equilibrium in the food chain and grazers of the algae can afford to be nonselective in their feeding behavior. This activity reduces grazing on less desired plants, and eutrophication can result (Conover, 1976). In this sense, selective feeding is analogous to intensive production, and nonselective feeding is analogous to extensive production.

It is the goal of a culturist using wastewater streams to have economic feasibility and achieve a desirable balance between wastewater treatment objectives and production of a marketable product. Until recently the use of aquatic organisms for wastewater treatment offered little apparent potential for food and fiber; however, the rising cost of fossil energy has emphasized the need for better alternatives.

Techniques to harvest algae from wastewater facilities have been extensively researched. Effective removal of plankton algae can produce a polished effluent of high quality. Selected references of Middlebrooks et al. (1974), McGarry and Tongkasame (1971), Golueke and Oswald (1965), and Friedman et al. (1975) discuss the harvesting techniques in detail. In general, most of the problems associated with mechanical harvesting are due to the algal cell size, cell density, and cell concentration in a large volume of water.

Middlebrook et al. (1974) listed the following processes for algae harvesting:

1. Centrifugation
2. Microstraining
3. Coagulation - Flocculation

4. In-pond removal of particulate matter
5. Complete containment
6. Biological disks, baffles, and raceways
7. In-pond chemical precipitation of suspended matter
8. Autoflocculation
9. Biological harvesting
10. Oxidation ditches
11. Soil mantle disposal
12. Dissolved air flotation
13. Granular media filtration
14. Intermittent sand filtration

If algae are to be used as a direct source of food or as feed for livestock, it must be cleanly harvested. It must be relatively free from harmful material and foreign matter such as sand and filtration aids that have been used to collect the algae. The technical expertise of personnel and costs generally determines the recommendations for algae separation. Centrifugation can remove 50 to 95% of the solids and concentrate the algae to 15 to 40% of the solids; some equipment for centrifugation has been cited as unreliable, expensive, and unsuitable for farm application. The power consumption for centrifugation was reported to be almost entirely a function of the amount of liquids processed at concentrations less than 1,000 mg/ℓ of solids (Golueke, 1977).

Microstraining rotating drums with 23- to 60-μm openings can remove an average of 89% of the plankton. Cleaning is usually required periodically, and only practical experience can determine the frequency. Processing rates have been reported to be between 210,000 to 703,000 ℓ/hr/m^2 (5,150 to 17,250 gal/h-ft^2). The associated economics and ease of operation make microstraining one of the more attactive methods for algal harvesting.

Sand filters are among the oldest methods for removing suspended solids from treated waste water. They can produce effluent of high quality, with BOD and suspended solids of less than 5 mg/ℓ. Their main problem is the speed at which water can be filtered and intermittent plugging of the filter which requires backwashing or renovation of the filter bed. However, if sand filtration is used in conjunction with rooted aquatic macrophytes, their potential for nutrient removal and suspended solids removal would be enhanced.

Biological "harvesting" with fish and invertebrates (crustaceans, mollusks, etc.) offers significant potential. However, the increased nutrient turnover rate, large land areas required, cultural management, and fecal decomposition complicate the engineering aspects of the treatment process. Therefore, this approach to wastewater treatment has not been readily adopted to substitute for more energy-consuming processes that were developed to treat large volumes of waste water.

Much of the information for nutrient removal rates and water quality improvement using "biological harvesters" (herbivores, filter feeders, or grazers) has been obtained with maximum production goals determined by the experimental design. Attention has been given to management of the culture for best control of dissolved oxygen, diseases, and water flow rates.

Maximum protein production is not generally considered practical for a one-step water treatment system. However, maximum protein production in biological waste treatment systems can effectively reduce the total amount of nutrients and suspended solids that must be processed for water treatment. If used in an integrated system where water treatment is a co-objective, biological waste treatment offers a viable alternative to the completely nutrient-destructive processes practiced in wastewater treatment which are very costly to taxpayers, owners of livestock, and industrial enterprises.

Algae growing in natural ecosystems can have a crude protein content between 30 to 50% on a dry-weight basis. Protein content of 13 species of freshwater algae ranged from 10.50 to 46.35 g/100 g dry weight, and amino acid content was very similar for these species (Boyd, 1973). Composition of Scenedesmus and Spirulina is compared to soybean meal in Table 1.

TABLE 1. COMPOSITION OF SCENEDESMUS AND SPIRULINA COMPARED TO SOYBEAN MEAL (PERCENT OF DRY WEIGHT) (SOEDER, 1976)

Cellular component	Scenedesmus	Spirulina	Soybean
Water	4-8	10	7-10
Crude protein	50-56	56-62	34-40
Lipids	12-14	2-3	16-20
Carbohydrates	10-17	16-18	19-35
Crude fiber	3-10	-	3-5
Minerals	6-10	4-6	4-5

The mineral composition of 14 genera of freshwater algae has been studied by Boyd and Lawrence (1967). Considerable variation was observed, but phytoplankton had lower metal ion content and higher carbon, nitrogen, and phosphorus levels than nonplankton species. Species were identified which contained at least one of the following minerals in higher than usual concentrations: nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, sodium, and boron. Copper, zinc, iron, and manganese were found to be high relative to terrestrial plants in most species tested. Therefore, the dominating species in an algal production system may be able to concentrate certain micronutrient elements.

Feeding trials with animals and tests with people were reviewed by Boersma et al. (1974). Processing algae is necessary to increase digestibility and palatability for maximum benefit, especially for monogastric animals. Digestibility values range from 40 to 80% for most animals tested and are well suited for chicken feed and carp feed. Waste-grown algae are generally considered unsuitable for human consumption due to its potential health hazard and poor digestibility and palatability.

FISH

The concept of growing fish in waters enriched with organic manures originated with the Chinese several thousand years ago (Bardach, 1972). The Chinese also developed the "polyculture" concept of growing several species of fish of differing food habits in the same body of water to more efficiently utilize the existing fish food. Polyculture entails use of efficient culture fish combinations and correct stocking densities (Hora and Pillay, 1962; Lin, 1954; Swingle, 1968; Tang, 1970; Yashouv, 1972; and Yashouv, 1966).

Several of the Chinese carps and tropical cichlids (tilapia) have proven efficient for polyculture combinations. The silver carp, bighead carp, and several of the tilapias have special anatomical structures which allow them to filter fine particulate matter from the water column (Greenwood, 1953; and Wilamovski, 1972). Henderson (1975) discussed the possible contribution of the bighead and silver carp to fish culture and concluded that because of their fast growth rate and ability to utilize pond food organisms otherwise underutilized, they would be compatible with catfish-polyculture operations in the U.S. Cremer and Smitherman (1975) studied food habits of the silver and bighead carp and found that the silver carp feed almost exclusively upon phytoplankton in the size range 8 to 100 µm, with the majority of the organisms in the range 17 to 50 µm, while the bighead carp feed primarily on zooplankton, phytoplankton, and detritus in the size range 17 to 3,000 µm with the majority of the ingesta in the size range 50 to 100 µm. Several of the Chinese carps are riverine fishes and do not spawn under pond culture conditions; however, inducement to spawn can be achieved by hormone and pituitary injections (Bailey and Boyd, 1970).

Cichlids of the genus Sarotherodon (formerly Tilapia) are also efficient filter-feeding culture fish (McBay, 1961; Shell, 1968; and Swingle, 1960) and are able to entrap small organisms (phytoplankton and zooplankton) in pharyngeal mucilage (Greenwood, 1953). In addition to feeding on phytoplankton and zooplankton, tilapia also actively graze benthic invertebrates and detritus (McBay, 1961).

Fish which feed low on the food chain and which have shown potential in waste recycling include common carp, goldfish, golden shiner, fathead minnow, grass carp, milkfish, and mullet.

Utilization of sewage and manures in fish culture is well documented (Allen, 1970; Allen, 1969; and Hickling, 1962). Yield trials have been conducted where animal manures were used as a supplemental source or the sole source of nutrient enrichment. Rappaport et al. (1977) reported that in monoculture yield trials tilapia or common carp stocked at 20,000 fish/ha (8,090/Ac) with chicken manure applied at the rate of 5 kg dry matter/ha per day as a supplemental source of nutrient enrichment outproduced the control (feed and inorganic fertilizer) by 17 to 24%. Use of chicken manure reduced the feed conversion ratio (FCR) by 0.8 unit and lowered the feed and fertilizer cost per kilogram of fish produced by 52%. Fish yield on a daily basis for the chicken-manure-enriched treatment was 36 kg/ha (32 lb/Ac) per day.

Moav et al. (1977) used liquid cow manure (12% dry matter) and a standard inorganic fertilizer treatment to produce 4,121 kg/ha (3,676 lb/Ac) in 126 days, or 32.6 kg/ha (29 lb/Ac) per day. Daily manure application rates ranged from 250 ℓ/ha (26.7 gal/Ac) per day early in the culture period to 1,750 ℓ/ha (187 gal/Ac) per day near the end of the culture period. For each 2.7 kg of dry weight manure used, 1 kg (2.2 lb) of fish was produced. This conversion ratio is comparable to feed conversion ratios reported for costly high-protein pelleted feeds. Also carp grown on manure had a body fat content of 6.2% as compared with 20% for carp grown on high-protein pellets.

Yield trials comparing production of all-male tilapia hybrids using cattle manure only or fed a commercial diet only have been conducted at Auburn University (Collis and Smitherman, 1978). Isonitrogenous amounts of manure or commercial feed were used twice daily at 3% of their body weight. Over a 103-day culture period, 28,381 kg/ha (25,316 lb/Ac) of fresh manure containing 5,392 kg/ha (4,809 lb/Ac) dry matter produced an average yield of 15.7 kg/ha (14 lb/Ac) per day as compared with 25.3 kg/ha (22.6 lb/Ac) per day for treatments fed a commercial diet. Analysis of stomach contents showed that some manure was used directly as a feed. However, taste evaluations showed no significant difference in taste and texture between fish sampled from treatments receiving manure or the commercial diet.

Lu and Kevern (1975) determined the feasibility of using various waste products as supplements to fish feeds. A pelleted ration consisting of 30% dried poultry waste and 70% salmon feed was fed daily to goldfish at 3% of body weight. After 5 months the control fish (100% salmon feed) exhibited a net increase of 475%, as compared with 627% for fish grown on the experimental diet.

In the same study, channel catfish were fed experimental pelleted diets consisting of 30, 70, and 100% dried poultry waste, respectively, at 2, 3, and 4% of body weight. Of the experimental rations, the 30% diet produced the best growth, exhibiting net gains at 2, 3, and 4% of body weight of 405, 367, and 501%, respectively, after 5 months. Control diets (100% salmon feed) fed at comparable rates exhibited net gains of 592, 941, and 1,065%, respectively.

Growth responses of blue tilapia (Sarotherodon aurea) to feed supplemented with dried poultry waste have been reported (Stickney et al., 1977). Tilapia that were fed for a period of 10 weeks at 3% of body weight daily on a commercial trout diet (control) and a trout diet supplemented at 10, 20, and 30% with dried poultry waste (DPW) demonstrated decreasing rates of growth as a function of increasing DPW levels. However, food conversions were outstanding for fish reared on the control and 10% DPW-supplemented diets. Even the poorest food conversion value obtained (1.40 from fish reared on the 30% DPW-supplemented diet) was excellent compared with other species of fish or livestock.

Konefes and Bachmann (1970) stocked a municipal sewage oxidation lagoon having a surface area of 494 m^2 (5,317 ft^2) with 3,800 fathead minnows with a mean length of 18.6 mm (0.73 in.). After 80 days of culture, the fish averaged 57.6 mm (2.26 in.) total length. Growth and reproduction of the minnows were comparable to that previously reported for hatchery ponds.

Coleman et al. (1974) stocked channel catfish, golden shiners, and tilapia into a series of municipal sewage oxidation lagoons at Quail Creek, Oklahoma. After four months of culture, the standing crop of catfish had increased from 273 to 2,000 kg (601 to 4,409 lb), the tilapia from 1.8 to 75 kg (4 to 165 lb), and the golden shiners from 39 to 243 kg (86 to 536 lb).

Hepher and Schroeder (1977) described a municipal wastewater utilization project in Israel which produced an average of 8,200 kg/ha (7,400 lb/Ac) of fish (polyculture) per 8 months (34 kg/ha [30 lb/Ac] per day). Ponds receiving waste water yielded 70% more than ponds not receiving such wastes. Additionally, 40% less supplemental feed was required to grow one unit of fish in the wastewater-enriched ponds compared to the ponds without such enrichment.

WATER POLISHING

Vascular aquatic plants are receiving much interest for their use in treating waste water where land and climatic conditions permit (National Academy of Sciences, 1976; Seidel, 1976). Some information is available on nutrient uptake rates and productivity in natural stands and waste-grown aquatic plants. Very little information exists on temperature responses of various aquatic vascular plants and their response to waste fertilization.

Productivity and yields in pure stands of aquatic macrophytes often equal or exceed those for terrestrial plants (Boyd, 1968). Boyd (1972) published a bibliography that contains many articles on chemical composition, nutritive value, nutrient removal, productivity and yield, ecology and life history, identification, nutrition, physiology, and nutrient cycles in aquatic communities. Standing crop, productivity, and yield for four common species in natural ecosystems of the Southeast are shown in Table 2. The protein requirements of approximately 300 people could be supplied by 1 ha (2.5 Ac) of water willow (*Justica americana*) (Boyd, 1970). Water hyacinth (*Eichhornia crassipes*) has one of the highest rates of growth reported, with 600 kg of dry matter/ha (535 lb/Ac) per day when fertilized with sewage effluent (Wolverton et al., 1976).

Water content of aquatic macrophytes (85 to 95% water) complicates their use for food and livestock feed (Boyd, 1968; 1970). Many aquatic plants are equal to or better than usual forages for livestock, having lower tannin content and higher protein than traditional forage, but they must be dewatered or dried before storing for feed.

The chemical composition of aquatic macrophytes is drastically affected by the nutrient level of their aquatic environments. Luxury consumption of phosphorus was observed in water hyacinth, and maximum growth occurred in acidic water (pH = 4.0) with 20 ppm phosphorus (Haller and Sutton, 1973). Ash content, mineral composition, and nutritive quality all vary with seasonal changes (Boyd, 1970) and growing conditions (Seidel, 1976). Water hyacinth is known to concentrate heavy metals and has been used to recover such valuable metals as gold and silver (National Academy of Sciences, 1976).

TABLE 2. STANDING CROP, PRODUCTIVITY, AND YIELD DATA FOR FOUR SPECIES OF AQUATIC VASCULAR PLANTS (BOYD, 1970)

Species	Standing crop (dry metric tons/ha)	Maximum productivity (dry g/m^2-day)	Maximum yield (metric tons/ha-yr)
Eichhornia crassipes (water hyacinth)	12.8	14.6	54.7
Justicia americana (water willow)	24.6	31.1	113.5
Alternanthera philoxeroides (alligator weed)	8.0	17.0	62.0
Typha latifolia (cattail)	15.3	52.6	192.0

Many other uses for aquatic macrophytes have been found and are practiced in many countries (National Academy of Sciences, 1976). Composted aquatic plants are used for fertilizer and to improve soil texture. Rumania uses reeds and rushes for pulp, paper, and fiber. Furniture, thatch, mats, boats, baskets, clothing, etc., are made from reeds and rushes in many parts of the world. Additionally, they can be used to feed herbivorous fish, aquatic animals, and waterfowl, or provide the raw material for methane gas production.

Wastewater treatment methods with aquatic macrophytes have been divided into four groups: water hyacinth, submerged plant, floating plant (duckweed), and the emergent plant. Golueke (1977) elaborated on these methods. Water hyacinths are used to treat the sewage of Lucidale, Mississippi (population 2,500); and NASA's National Space Technology Laboratory is cooperating with Mississippi State University in cattle feeding trials with the hyacinths. Wolverton et al. (1976) have reported 20 to 40 metric tons/ha (9 to 18 tons/Ac) of wet water hyacinth could be harvested per day while removing the nitrogen waste of over 2,000 people and the phosphorus waste for over 800 people. Steward (1970) reported that water hyacinth removal rates could treat nitrogenous waste of 595 people and phosphorus from 180 people per 0.4 ha (1 Ac). Rogers and Davis (1972) reported 1 ha (2.5 Ac) could absorb the nitrogen and phosphorus of over 500 people. The removal efficiencies reported by Wolverton et al. (1976) for water hyacinth and alligator weeds during 7-day exposures to sewage are given in Table 3.

TABLE 3. EFFECT OF WATER HYACINTH AND ALLIGATOR WEED ON CERTAIN WATER QUALITY CHARACTERISTICS

Water quality measurement	Water hyacinth (*E. crassipes*)	Alligator weed (*A. philoxeroides*)
	Percent Removal	
Total nitrogen	92	97
Total phosphorus	60	50
Total suspended solids	75	98
Biological oxygen demand (BOD_5)	97	92

Water hyacinth reduced the chemical oxygen demand of swine waste water and stripped 78% of the total nitrogen and 72% of the phosphate-P from test pools in Iowa from June to September (Miner et al., 1971).

Bagnall et al. (1974) reported on the potential for water quality improvement using water hyacinth grown on secondary treated effluent. Five-day water retention times removed 80% of the nitrogen and 60% of the phosphorus; however, only 10% of the nutrients were found in plant tissues. It was recommended that 25 to 33% of the plants should be harvested per week to maintain optimum growth and nutrient removal. It was concluded that compost could be produced from water hyacinth for about $3.30/metric ton ($3/ton) and sold for about $50.60/metric ton ($46/ton) (1974 prices). Cattle and sheep feeding trials produced satisfactory results using up to 25% water hyacinth (dry) in the complete diet. The profit margin was estimated to be very small if water hyacinth was processed dry for feed. Its properties were found to be unsatisfactory for producing paper pulp.

Harvesting of large volumes of aquatic waste weeds for forage processing or composting is a problem. Engineering designs for increasing mechanical harvesting rates are still evolving. Water weeds are bulky and heavy due to their high water content, and any system for harvesting and processing must be mobile and waterborne (Bagnall, 1977; Koegel, 1976).

Submerged plants such as *Hydrilla verticullata* and *Ceratophyllum demersum* can be used to treat waste water. This method must have sufficient oxygen and sunlight penetration to support the submerged plants, as plants grown in this manner are more difficult to harvest. Herbivorous fish (e.g., grass carp), crayfish, and waterfowl could be used to harvest these plants. Caution is required to prevent introduction of such noxious weeds as hydrilla into navigable waterways and streams. McNabb (1976) has used native species of Potamogeton, Ceratophyllum, or Elodea to treat waste in aerobic stabilization ponds in Michigan. It was recommended that 50% of the maximum standing crop be removed at 14-day intervals for four or five cycles during the season.

The family Lemnaceae comprises small, flowering, and floating vascular plants with about 40 species represented by the genera Wolfiella, Wolffia, Spirodela, and Lemna. These floating plants are easily harvested and exhibit a wide range of thermal tolerance. Several species are commonly used for human food in Southeast Asia (National Academy of Sciences, 1976) and make excellent food for ducks, geese, poultry, swans, herbivorous fish, cattle, and pigs (Culley and Epps, 1973; Truax et al., 1972). Grown on livestock waste, Spirodela oligorhiza and Spirodela polyrhiza have doubled their biomass every three days and produced 500 kg/ha (446 lb/Ac) of dry matter per day during a 9-month growing season. One hectare of duckweed at this growth rate could produce crude protein equivalent to 60 ha (148 Ac) of soybeans.

A recent study in Louisiana has indicated the nutrient recovery rate per hectare of duckweeds was equivalent to the manure nitrogen of 15.5 head of dairy cattle, manure phosphorus of 34 head, and manure potassium of 8.8 head. Annual yield was estimated to be 22,023 kg (4,856 lb) of dry weight with a mean crude protein content of 36% (Myers, 1977).

Duckweeds have production limitations. Waste-heated water could possibly extend the growing season in the cooler months, if warm water was made available to the production system. Typical of aquatic macrophytes, duckweeds contain 90 to 95% water, making transportation and processing into dry feed difficult. They are easily moved by wave and wind action. Some species of Lemna contain large amounts of oxalic acid which may limit their use in animal feeds. While their vegetative reproduction gives rise to high yields, their cultivation can lead to a narrow genetic base as sexual reproduction is rare. This can limit obtaining geographical reproducibility of production, if careful selection of vegetative clones is not practiced.

Seidel (1976) has recently reported on the patented developments at the Max Planck Institute in West Germany. They have developed emergent aquatic plant systems to treat municipal waste and certain industrial waste water, some with high concentrations of phenols, dyes, and cyanogen. This institute continues to survey plants for potential applications for specialized treatment. The bulrush (Schoenoplectus lacustris Palla) and reeds (Phragmites spp.) are used in the treatment system.

In this type system, sludge is trapped and decomposed on a gravel bed planted with Phragmites. The plant roots drastically reduce the soluble organic pollutants and the bacterial counts. Additional treatment with bulrushes is achieved on sloping gravel beds. Bulrushes normally shed their roots each year but do not shed them in the sewage treatment system. The roots excrete substances which neutralize the pH to near 7, and these excretions are believed to be toxic to pathogenic bacteria. A high degree of treatment is achieved through the growing months; however, the metal and mineral adsorption varies greatly with the environment and type of sewage. The removal rate of heavy metals must be measured on a system. Tidal inundation is practiced to assure proper dissolved oxygen levels and to assure even applications of sewage to the root zone. The following guidelines were given when designing an emergent plant water treatment system:

1. Use inert material for filtration and rooting media, e.g., sand or gravel.

2. Design to provide adequate oxygen to root zone. Use the tidal inundation system to assure even application to plant beds.

3. Guard against excessive algae blooms to prevent rapid clogging of filters and anaerobic conditions.

4. Spread effluents on to narrow beds, making it possible to harvest stems from the banks.

5. Harvest shoots periodically and timely to obtain optimum nutrient removal rates. Do not disturb the beds.

6. Know sewage composition and plan for specialized pretreatment, if necessary, to prevent certain industrial wastes from damaging the biological system.

A similar system is used in Holland (de Jang, 1976) to treat waste from beaches and summer camping sites. These systems produce annual harvests equivalent to 35 to 50 kg/ha-yr (31 to 45 lb/Ac-yr) of phosphorus and 260 to 270 kg/ha-yr (232 to 241 lb/Ac-yr) of nitrogen. Ten-day retention times gave removal rates of 98% BOD, 95% total nitrogen, 93% total phosphorus, and 98% removal of total coliforms, which exceed the treatment capabilities of trickling filters and activated sludge systems for Dutch situations. The bulrush foliage has been used for compost material, wicker material, and livestock feed (Pomoell, 1976).

Many other aquatic plants may have potential for recycling of food or fiber from wastewater streams. The reader is referred to the publication by the National Academy of Sciences, *Making Aquatic Weeds Useful: Some Perspectives for Developing Countries* (National Academy of Sciences, 1976). Some of those that may have potential food value are: water spinach (*Ipomoea aquatica*), watercress (*Nasturtium officinal*), floating rice (*Oryza sativa*), wild rice (*Zizania aquatica*), lotus (*Nelumbo hucifera*), Chinese water chestnut, (*Eleocharis dulcis*), taro (*Colocasia esculenta*), swamp taro (*Cyrtosperma chamissonis*), arrowhead (*Sagittaria trifolia*), and azolla ferns (*Azolla pinnata*).

WATER QUALITY

Wastewater research has shown that several aquatic bio-recycling systems have the potential for treating waste water as an alternative to more expensive conventional physicochemical methods (Jong, 1976; Seidel, 1976). Lin (1974) and Prowse (1969) proposed using finfish as a means of controlling eutrophication. Schroeder (1975) discussed the effects of stocking fish in oxidation or sewage lagoons. Without fish, the lagoons were in a state of ecological imbalance as the cyclic buildup and sudden decline of phytoplankton populations resulted in the system going from aerobic to anaerobic, and massive dieoffs and decomposition of phytoplankton reduced dissolved oxygen to a level where the operational capacity of the pond to oxidize organic wastes was severely impaired. The addition of fish to the oxidation ponds resulted in reduced but stable phytoplankton populations, reduced benthic populations, increased diurnal oxygen concentrations, increased pH, and reduced bacteria populations by as much as 15 times when compared with the "no fish" control. High pH and dissolved oxygen levels improved the operation of the oxidation pond to provide an effluent low in BOD, nutrients, and bacteria.

Caldwell et al. (1975) reported that of 9,951 municipal secondary treatment systems in the United States, approximately 35% utilized stabilization lagoons. The Environmental Protection Agency has suggested that limits for BOD and suspended solids from secondary treatment be less than 30 and 45 mg/ℓ on a monthly and weekly average, respectively. With these stringent effluent requirements, several of these oxidation lagoons may need modifications as suggested by Caldwell et al. (1975) to meet effluent standards.

Henderson (1977) evaluated silver carp and bighead carp as bio-filters for water quality improvement. These fish were stocked into a series of sewage treatment lagoons with a series of control lagoons remaining unstocked for comparison. Results showed consistently lower coliform bacteria counts in ponds stocked with fish; and, on an annual basis, stocking of fish in the lagoons resulted in an additional decrease in BOD (37.6%), a reduction in ammonia nitrogen (27%), and a reduction in orthophosphate concentrations (2.72%).

Elevated pH, as a result of intense photosynthesis (Rutner, 1963), may result in direct mortality of fish (Amlacher, 1970; and Tennessee Valley Authority, 1978) or cause mortality indirectly as a result of toxic concentrations of unionized ammonia being formed at elevated pH values (Allen and Carpenter, 1977; Spotte, 1970). High pH values associated with intense photosynthesis in wastewater lagoons increase the disinfection capacity of those lagoons (Oswald, 1972). Carpenter et al. (1974) reported that no pathogens were isolated past cell 2 in a 6-cell series of sewage-oxidation lagoons (2.43 ha/cell, 13-day retention/cell) in which fish were grown. Other investigators have also reported excellent disinfection by the lagoon method (Drew, 1966; Okun, 1962).

Oxygen depletions may result from massive dieoffs of phytoplankton resulting in high biological oxygen demand (Boyd et al., 1975) or from decay of organic matter being placed in the pond as an organic fertilizer (Schroeder, 1974). Hepher and Schroeder (1977) and Schroeder (1975, 1974) discuss the use of organic manures, BOD of manures, sizing of fish ponds to receive such wastes, and efficient methods of aeration to prevent oxygen depletions.

Organisms produced in systems using municipal sewage or animal manures may accumulate pathogens, heavy metals, or toxic organic materials. This problem needs to be resolved. Literature reviews discussing these problems are available (Huguenin and Kildow, 1974; Janssen, 1970; Kildow and Huguenin, 1974; Shuval, 1977; and Tsai, 1975).

The World Health Organization (1973) recommended a 30-day retention time to achieve a 99% reduction in microbial pathogens. Stanford and Tuburan (1974) did not find any cases of a disease resulting from use of treated sewage products when the treatment plant was operating within its design capacity. Byran (1974) stated that if contaminated foods were cooked at 73.8°C (165°F) for sufficient periods of time, vegetative bacterial cells, protozoa, helminth eggs, and most viruses would be killed.

Kerfoot and Jacobs (1974) and Kerfoot and Redmann (1974) recommended permissible levels of heavy metals in secondary treated effluent for use in a combined sewage treatment-marine aquaculture system. Their recommendations (as ppm in effluent) were to not exceed: 0.5 (Cr), 1.0 (Pb), and 1.0 (Zn) based on toxicity to algae; 0.20 (Cu) based on acute toxicity to humans; 0.010 (Cd) based on chronic toxicity to humans, and 0.05 (Ni) based on pollution alert levels. They warned, however, that total metal content may be misleading since the structures of many of the complexed compounds are not well known.

The University of California at Los Angeles studied the movement of heavy metals in a wastewater nutrient recycling system and found that the planktonic algae Scenedesmus concentrated all heavy metals monitored (Cd, Pb, Cr, Cu, Mn, Zn, and Ni) by factors ranging from a few hundred (Cr and Ni) to several thousand times (Mn, Cu, Pb, and Zn). The elevated heavy metals concentrations observed in the algae declined slightly in cladocerans (Daphnia) and sharply in fishes (fathead minnows and golden shiners) (Dong and Gordon, 1977).

Allen and Carpenter (1977) described results in which water quality was monitored in a series of oxidation lagoons with fish, and later, without fish. Their results are presented in Table 4.

Results showed that in all parameters measured, the system with fish performed better in terms of wastewater treatment when compared with the system without fish. It was concluded that proper lagoons (not overloaded) reduced human pathogens well below the current EPA standards. Meeting low bacterial requirements with the lagoon method emphasizes the possibility of eliminating expensive chlorination as well as dechlorination units.

The polyculture concept in conventional fish culture also benefits water quality. In intensive pond culture of channel catfish, up to 4,500 kg/ha (4.014 lb/Ac) of high-quality protein feed is fed per 7 months of culture. Nutrient assimilation by the catfish accounted for 25% of the available nutrients in the feed, while 75% of the nutrients reached the water as wasted feed or fish excrement (Boyd, 1974). Mineralization of these wastes results in high BOD, COD, and fertility levels (Ruane et al.,

TABLE 4. COMPARISON OF MEAN VALUES OF SELECTED WATER QUALITY PARAMETERS IN THE TERMINAL UNIT OF A SIX-UNIT LAGOON WASTEWATER TREATMENT FACILITY AT QUAIL CREEK, OKLAHOMA

		Terminal lagoon		
Water quality measurement	Raw sewage 1 Mgd	With fish	Without fish	Current EPA standards
BOD_5 (mg/ℓ)	184	6	21	30
Suspended solids (mg/ℓ)	197	12	37	30
Total nitrogen (mg/ℓ)	19	3	10	-
Total phosphorus (mg/ℓ)	9	2	8	-
pH (standard units)	7.3	8.3	7.9	-
Fecal coliforms/100 ml	3×10^6	20	25	200
Sampling schedule	Weekly	Weekly	Biweekly	-
Sampling period	June- Oct. '73	June- Oct. '73	July '74- Apr. '75	-
Number of samples	17	17	13	-

1975). Excessive phytoplankton blooms resulting from elevated fertility levels can lead to oxygen depletions and fish kills during cloudy weather or following massive phytoplankton dieoffs (Boyd et al., 1975; Swingle, 1968). Mechanical aeration, recirculation, filtration, polyculture, and aquatic plant culture have been advocated as methods to enhance dissolved oxygen levels and/or reduce nutrient concentrations (Smitherman and Boyd, 1974), while significant water quality improvements in polyculture production ponds have been reported (Behrends, 1977; and Dunseth, 1977). Silver carp, tilapia, and catfish were stocked in polyculture at 2,470, 1,975, and 7,400/ha (1,000, 800, and 3,000/Ac), respectively. Polyculture treatments had significantly higher dissolved oxygen concentrations during critical early morning periods than the control (catfish monoculture). During the final two months of the growing season, phytoplankton volumes were significantly lower, and phytoplankton diversity values (a measure of ecosystem stability) were significantly higher in polyculture treatments than in the monoculture treatment. The persistent grazing of phytoplankton by silver carp resulted in phytoplankton communities dominated by small green algae, while those treatments without silver carp had phytoplankton communities dominated by larger blue-green algae. Henderson (1977) also noted a predominance of small green algae in sewage treatment ponds stocked with silver carp, while unstocked ponds were dominated by blue-green algae.

The utilization of waste heat from power plants and the use of organic manures for production of plants and animals present their own special problems. Schneider et al. (1975) reported ongoing work at the Pacific Northwest Laboratories on thermal responses to "cold shock," excessive temperatures, gas supersaturation, and the combined effects of heat and power plant chemicals routinely added to the water.

Gas supersaturation resulting from intense photosynthesis has been implicated in cases of gas bubble disease with attendant mortality (Allen and Carpenter, 1977; Renfro, 1963; and TVA, 1978). Vigorous aeration may help to alleviate this problem by achieving a normal equilibrium of gas pressure (Amlacher, 1970). An extensive literature review on gas disease in fish is available (Harvey, 1975).

Water quality criteria for integrated approaches such as proposed in this report would be considered on a case-by-case basis, when permitting was requested for a commercial operation. This study has assessed several water quality parameters and has made evaluations of how they are influenced by the treatment effects of both fish culture and rooted aquatic macrophyte culture which receives the fish waste water in the concept shown in Figure 1. For the purposes of discussion, secondary treatment standards for municipal waste water will be 30 mg/ℓ biological oxygen demand (BOD), 30 mg/ℓ suspended solids (SS), and 2 mg/ℓ total ammonia nitrogen (NH_3-N). Additionally, treatment standards of advance wastewater treatment shall be considered to be 1 mg/ℓ for each of the above-mentioned properties. Ranges of regulated dissolved oxygen (DO) and pH usually required of municipal waste treatment plants generally fall into the range of fish survival at DO = 5 to 8 mg/ℓ and pH = 5 to 9.

SECTION V

PRODUCTION TEST

The approach taken could produce useable biomass in the form of algae, fish, or plants produced in the plant-polishing phase of the proposed system. Total biomass produced in such an integrated system is difficult to account for in a mass balance budget. However, the influences and controls imposed on the system can be directly accounted for in the harvestable and useable biomass components. The concept depicted in Figure 1 has been developed by studying the algae, fish, and water polishing steps in a successive manner. Each component is interdependent, but some studies were conducted on the components as independent units.

The algae biomass produced can directly and indirectly affect the harvestable fish biomass in such a system. Therefore, it is beneficial to estimate some dynamic controls that can be used to manipulate the growth of algae to indirectly benefit the production of fish that feed upon the phytoplankton.

Primary emphasis regarding useable and harvestable biomass has been placed on the productivity of the fish system. However, this is an arbitrary decision since primary emphasis could be placed on a harvestable plant biomass. A plant system could be either aquatic or terrestrial. However, to take advantage of the CCW and its heat content, an aquatic plant system offers distinct advantages over a terrestrial or greenhouse system. Aquatic plants offer the potential for direct beneficial use of the CCW, avoid the need for costly heat exchangers and improve the water quality by removing potentially polluting constituents.

Choice of the aquatic plant in this integrated approach can serve to complement the fish biomass component because plants can be chosen which require different amounts of different fertilizer constituents than those required by the fish-algae system. The direct heat benefit to the plant-polishing aspect is minimized in this approach since the rate of heat used is limited by the biological processes in the fish culture. Therefore, a major benefit derived from producing biomass in the water-polishing component is the improved effluent water quality. This approach can serve to optimize the plant nutrient uptake and provides flexibility to place different degrees of emphasis on the production of fish or plant biomass as needed or demanded by the system. If fish production is to be maximized, then biomass produced in the plant-polishing phase must be optimized to have maximum benefit to the system. Therefore, the ratio of fish biomass to plant-polishing biomass is subject to change. Many things can influence this proportional relationship. Fish species, plant species, flow rates, water temperatures, source of manure, water quality, power plant requirements, marketing constraints, and production costs are some of the influential factors on the optimization approach.

ALGAE

Algae production rates were evaluated during 1976, 1977, and 1978. During 1976, the potential for microbial biomass production was estimated in outdoor cultures. These cultures were not heated, and pit-stored swine manure was used from a nearby farm. The effects of stirring, culture depth, retention time, seasonal changes, and manure dilutions were studied to estimate the culture requirements. Greater benefits of elevated water temperatures were anticipated during the spring and fall transition periods. Therefore, more emphasis was given to the growth of algae during these periods.

Depths of 13, 20, and 40 cm (5, 8, and 16 in.) were evaluated under static and stirred conditions. The highest rate of growth was achieved in 13 cm (5 in.) deep pools with continuous agitation, but this depth gave a wider variation in diurnal temperatures than did deeper pools (20 and 40 cm). With clear weather, 28° to 30°C (82.4° to 86°F) average daily water temperature, and continuous agitation, little difference in production was noted between the 20 cm and 40 cm deep cultures.

Cultures were fertilized with the supernatant from pit-stored swine-manure slurries to achieve initial NH_3-N concentrations of 8 to 10 ppm N. It was found that a 40 cm deep culture of 4,200 liters and an initial density of 25 to 50 mg/ℓ of algal biomass could reduce an initial NH_3-N level of 8 to 10 ppm to approximately 1 to 2 ppm in 2 days, but one cloudy day could cause a time requirement of 3 to 4 days (Figure 2). Algal densities were usually greater than 100 mg/ℓ of ash-free dry weight, 200 mg/ℓ of total dry matter, or several hundred million cells per liter. These algal slurries were used daily to feed the silver amur (Asiatic carp) when the NH_3-N level had been reduced to near 1 ppm. During late summer and early fall, 5-day growth periods proved to be the shortest and the most reliable time interval for producing high-density algal slurries with convenient volumes to transfer to fish tanks.

Green algae, _Kirchneriella_ _lunaris_ and _Kirchneriella_ _contorta_, initially dominated (94%). However, population successions were experienced and the dominant green algae population would evolve to _Oocystis_ _elliptica_ and other _Oocystis_ species during periods of cloud cover and cool temperatures

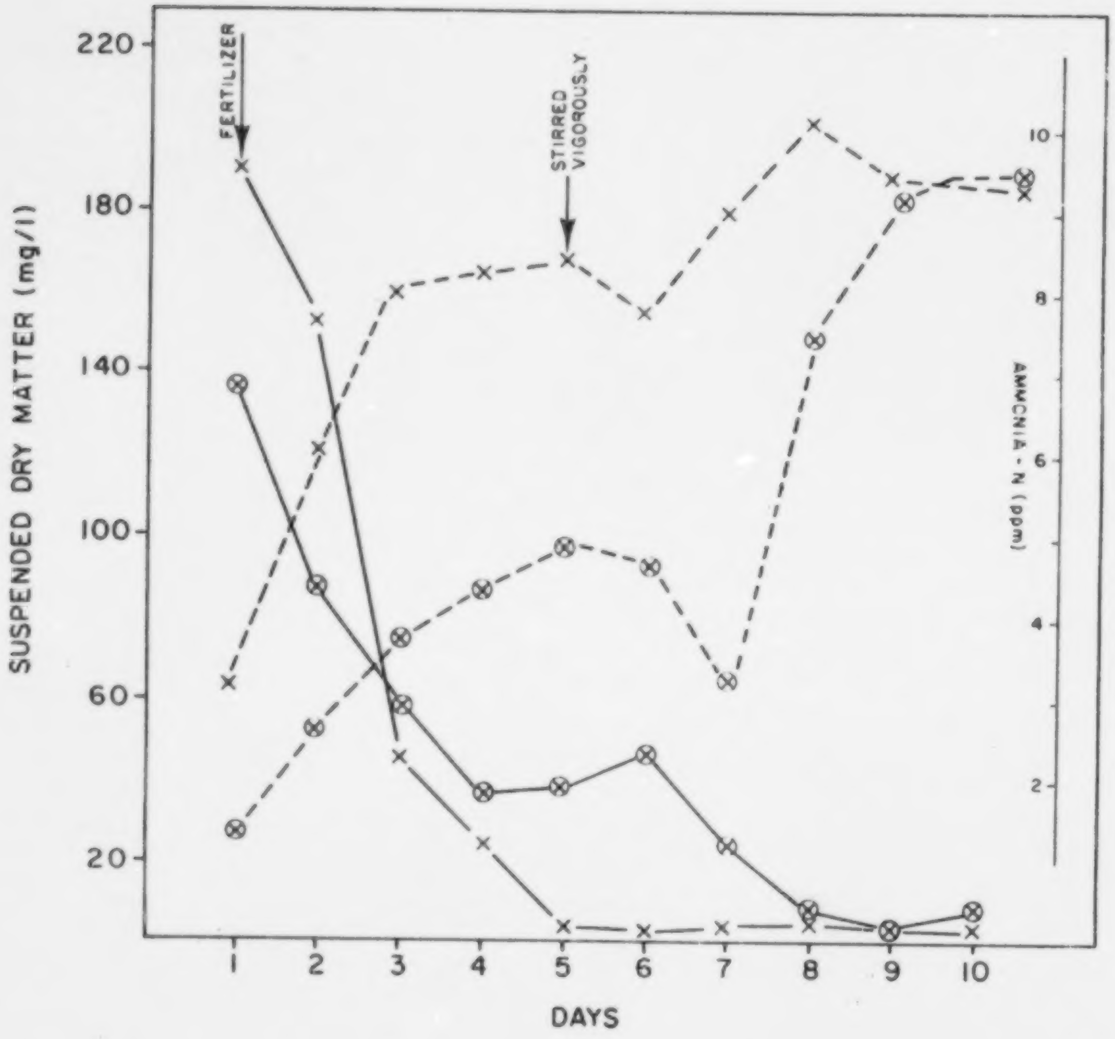

Figure 2. Growth of algae cultures and disappearance of NH_3-N at two temperature ranges. 25-30°C = X, 15-20°C = ⊗, NH_3-N = ———, and dry weight = ------, @ 40-cm depth during September 1976.

Growth of algae was studied with temperature control and greenhouse conditions during 1977. All tests were made under controlled stirring intervals, stirring speeds, and 34-cm depth. During the spring of 1977 a study was conducted to estimate the influence of swine manure dilution on algae growth rate, ammonia nitrogen reduction, and concentration of suspended solids. Table 5 illustrates the results achieved when 5-day retention times were used in March 1977 and water temperatures of 24.7°C (76.5°F) were used to simulate CCW from the Browns Ferry Nuclear Plant.

This study suggests that a critical level of manure exists wherein additional manure would inhibit the growth rate of plankton. This level was exceeded when manure was added at a rate of 1 liter per 170 liters of cultures. The growth rate was only 67% when compared with the growth rate at one-half the dilution rate (Table 5). Furthermore, this observed suppression of algae growth and standing crop (dry matter concentration) is dependent on culture temperature.

TABLE 5. EFFECT OF MANURE DILUTION ON AMMONIA, SUSPENDED SOLIDS, AND ALGAE GROWTH[a] [MARCH 1977, 24.7°C (76.5°F)]

Manure dilution	NH_3-N reduction mg/l-day	Suspended solids (mg/l)	Algae growth (g/m^2-day)
1:1360	1.9	86	11.7
1:907	2.1	95	13.7
1:680	3.0	130	20.6
1:340	3.9	139	26.8
1:170	5.0	137-174	18.1

a. Daylight stirred 12 h; 15.2 cm/sec. = average radial water speed.

Suspended solids (SS) concentrations in algae cultures were reduced at all temperatures tested when dilutions less than 340:1 were tested. Increasing the manure concentration from 1:340 to 1:272 reduced SS only 9% when cultured at 40.6°C (105°F), 31% at 29.4°C (85°F), and 46% at 24.4°C (76°F) (Table 6).

Algae grown at 105°F were predominantly blue-green (Oscillatoria). Crude protein was observed to be reduced in algae grown at 105°F when compared to lower temperatures. It was thought that algae quality could limit fish growth during periods of higher temperatures if the protein concentration was reduced in the algae as a result of increased algae respiration at the elevated temperatures. A series of tests were conducted to estimate the influence of algae growth and algae quantity as a result of temperatures and cultural conditions.

TABLE 6. EFFECT OF TEMPERATURE ON SUSPENDED SOLIDS AT THRESHOLD LEVELS OF MANURE DILUTION[a]

Water temperature °C (°F)	Manure dilution	Suspended solids	
		Achieved mg/ℓ	Percent difference
40.6	1:340	100	
(105)	1:272	92	8
29.4	1:340	145	
(85)	1:272	100	31
24.4	1:340	140	
(76)	1:272	76	46

a. Pit-stored manure March-April 1977.

During November and December 1977, growth of algae and changes in suspended solids concentration in fiberglass tanks (680 liters and 1.98 m^2) under a plastic greenhouse were studied. Water temperatures were maintained at 23.9°C (75°F), 29.5°C (85°F), and 35.0°C (95°F). Culture water was stirred during daylight hours to an average velocity of 15.2 cm/sec and maintained at a 34-cm depth. Batch culture growth with daily addition of swine manure was used until nearly constant concentrations of suspended solids (standing crop of algae) were observed (Figure 3). Suspended solids (SS) were considered "constant" when three consecutive days of measurements were within 10% of each other. At this point, cultures were then placed on daily discharge rates equal to the water retention days of the constant concentration. Constant SS concentration was achieved on the fifth day with 29.5°C (85.1°F) and on the ninth day at 23.9°C (75°F). The 35°C culture exhibited a highly variable SS but was maximum on the fifth day and was considered constant on the sixth day. The maximum observed SS was 122, 130, and 117 mg/ℓ for the 23.9°, 29.5°, and 35.0°C cultures, respectively. Growth rates of algae at this stage of growth were estimated to be 12.6, 18.5, and 21.7 g/m^2-day (0.5 lb/ft^2-day) for the 23.9°, 29.5°, and 35.0°C cultures, respectively (Figure 4).

Algae cell counts increased logarithmically over the first 5.5 days at a rate approximately equal to 2.47×10^6 cells/ml-day (Figure 4). During this period, the cells were larger in the 35°C (95°F) water. Maximum algal cell count was obtained on day five for the 35°C culture with 2.8×10^7 cells/ml. However, cell counts were maximum on day six for the 23.9° and 29.5°C cultures at 2.6×10^7 and 2.3×10^7 cells/ml, respectively. Two days of cloudy weather resulted in a depressed cell count on day nine, but dissolved oxygen reached a maximum after 8 days during a time when cell counts were declining rapidly (Figure 5). When compared with the maximum concentrations observed, the cell counts were 94, 84, and 61% of the maximum in the 35.0°, 29.5°, and 23.9°C cultures, respectively. Two days of heavy cloud cover had little effect on the observed standing concentration of

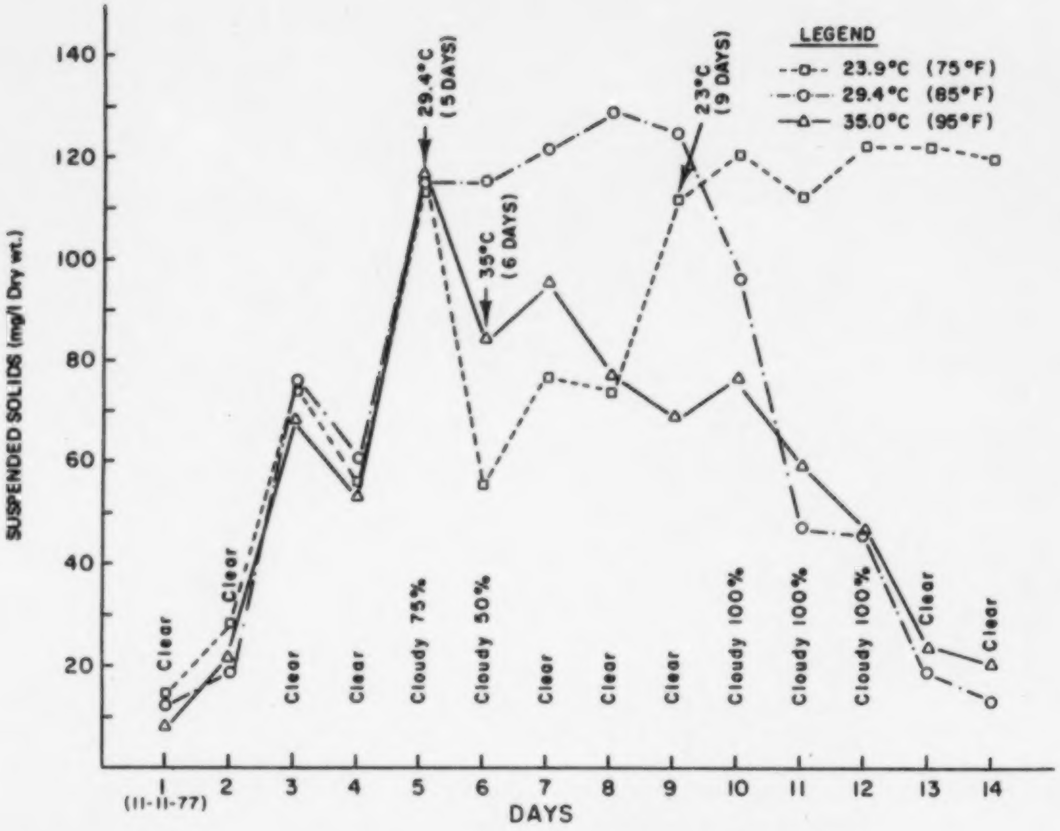

Figure 3. Influence of temperature on suspended solids concentration during cloudy and clear weather in the winter period (November 1977).

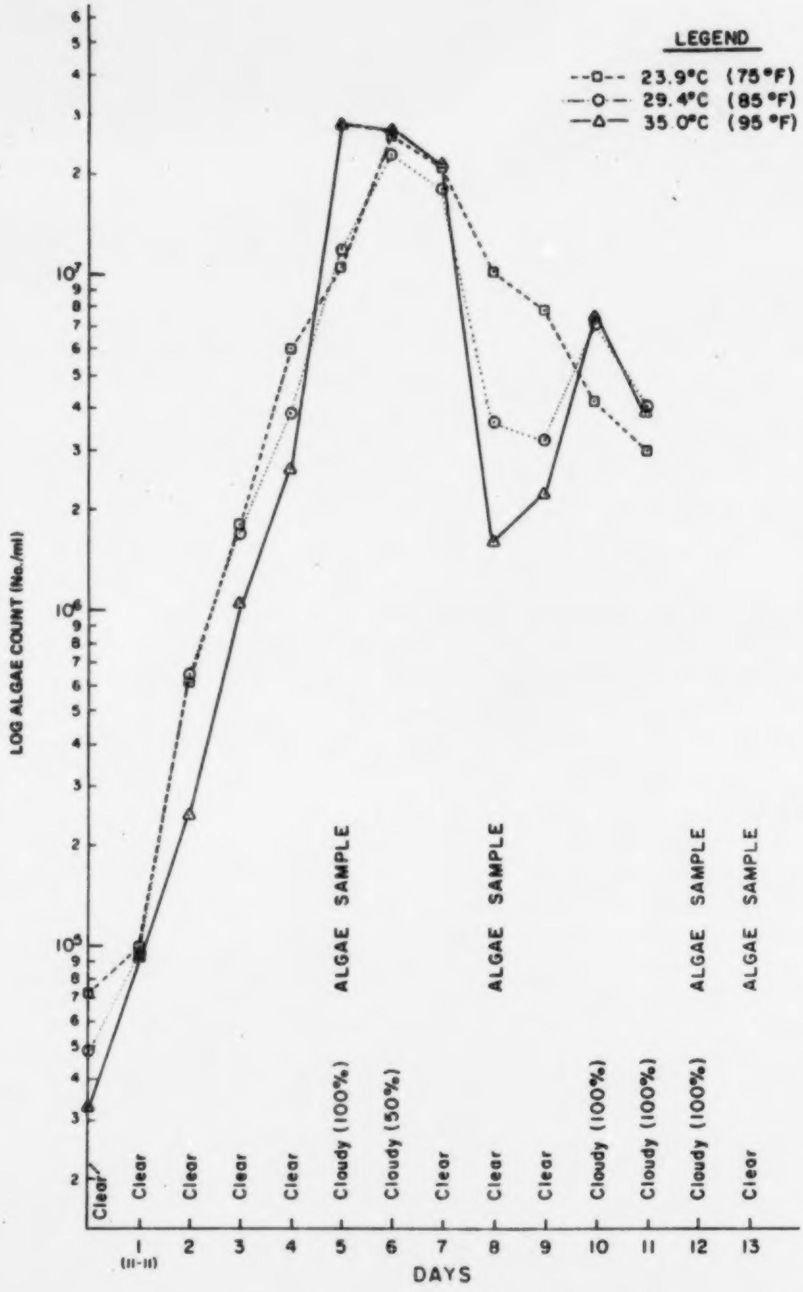

Figure 4. Algae growth (cells/mℓ) as a function of temperature and time during the "start-up" phase of algae cultures (November 1977).

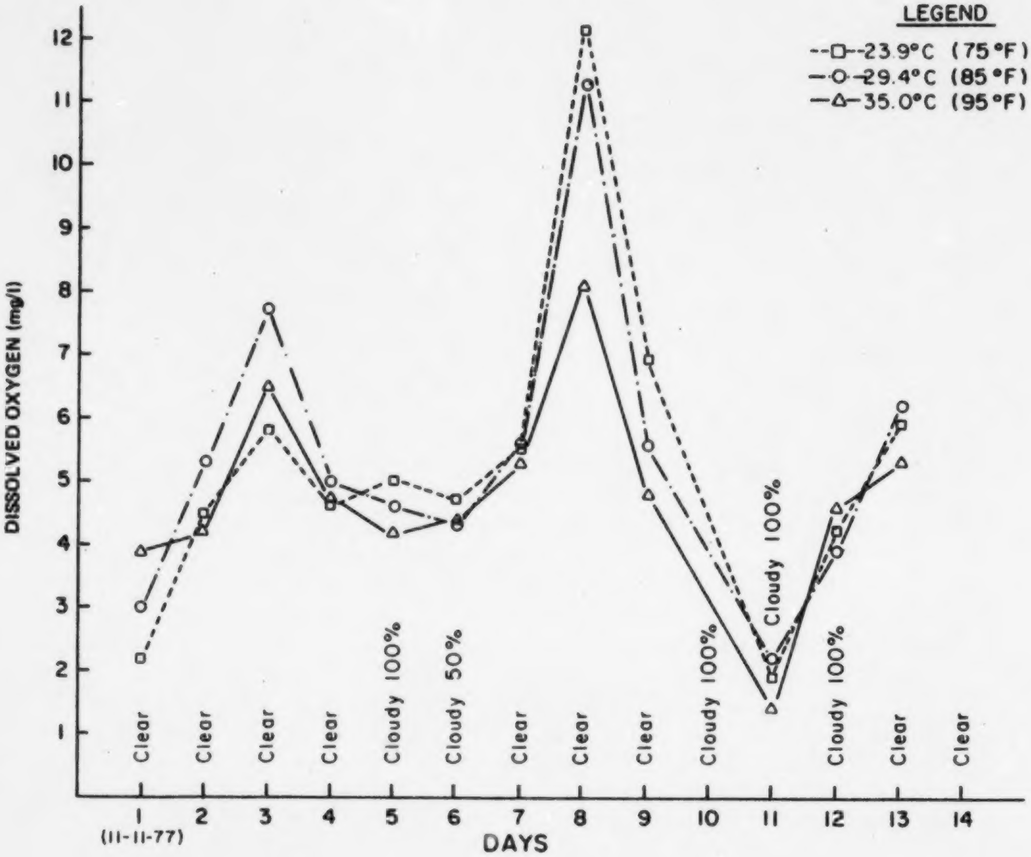

Figure 5. The observed morning dissolved oxygen content in growing algae cultures as a function of temperature and time during periods of cloudy and/or clear weather.

suspended solids, but the dry matter accumulation rates for the 23.9°, 29.5°, and 35.0°C were estimated to be near zero or less. Cell sizes during cloudy periods were larger in cooler cultures.

The change in total ammonia nitrogen is shown in Figure 6 for these algae cultures. Manure was added equally to the algae cultures for the first 5 days until the cultures attained concentration of approximately 20 mg/ℓ. The disappearance rate of ammonia nitrogen was less for the cooler (23.9°C) culture and was observed to increase on the tenth day. The maximum ammonia nitrogen level achieved was less in the warmest culture (29.4°C), and the level declined rapidly when manure was not added. More manure was required in warm water to achieve comparable levels of ammonia at cooler water temperatures. The rate of nitrogen disappearance would be greater in algae cultures grown in warm waters.

The data indicated that algae standing crops during the winter months can be severely curtailed by long periods of cloud cover (10 days). Cooler cultures under similar conditions appear to be more stable in growth but at a lower growth rate. Additionally, cell growth appears to be more prevalent in cooler cultures, while cell reproduction is more prevalent in warmer cultures. These temperature effects have been reported in marine species (Goldman, 1977).

Algae slurries were collected on selected days (Figure 3) and analyzed to determine levels of certain elements observed in the tissue. Algae slurries were differentially centrifuged through a sucrose gradient to purify the suspended solids and to obtain a nearly pure packed cell volume of 500 ml of algae. Algae cakes were washed in a sodium carbonate buffer and oven dried at 70°C (158°F) (Price, 1974).

Elemental content of the algal SS is given in Table 7. On the average, nitrogen content was 0.8% less in the 35°C (95°F) culture than the 23.9°C (75.0°F) culture. The nitrogen content (crude protein = 6.24 x % N dry weight) of the algae ranged ± 1% from the average during the growing period, but was not significantly different as a result of the temperature variable. Phosphorus content was subject to a wide range of variation during the testing period. Copper, zinc, and iron were more concentrated in the dry matter produced in the warmer water. Potassium, calcium, magnesium, sodium, and manganese were not significantly different at these temperatures.

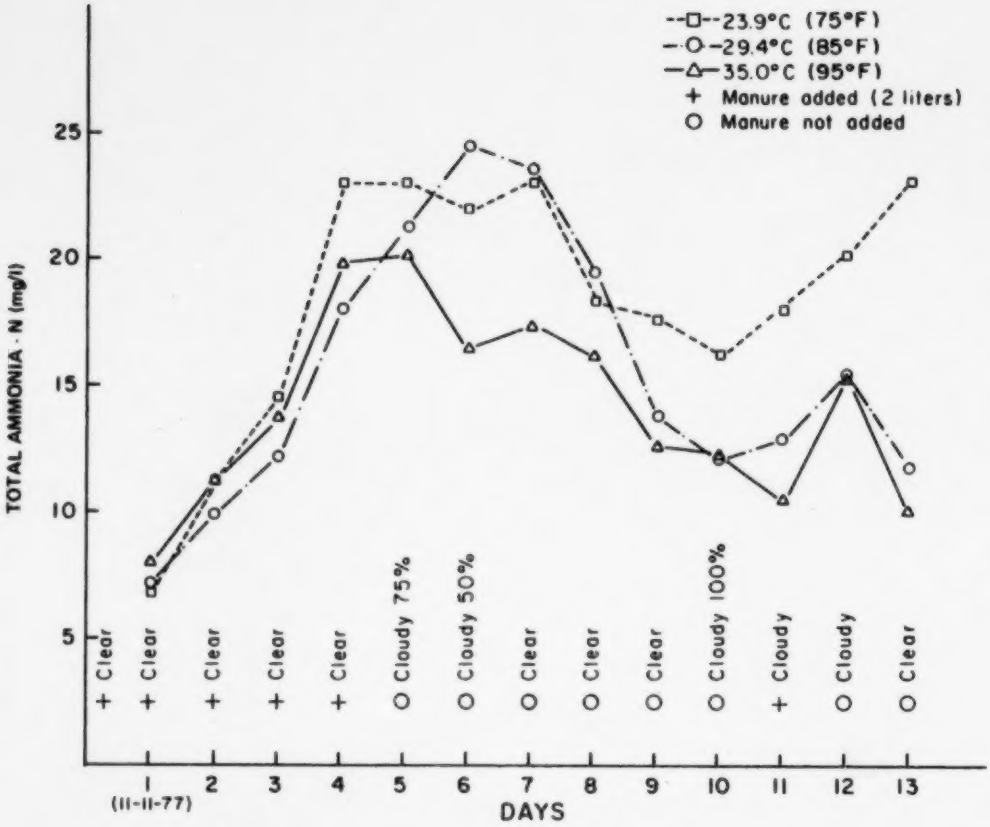

Figure 6. The change in total NH_3-N in algae cultures 24 hours after manure addition as a function of time and temperature.

TABLE 7. ELEMENTAL ANALYSIS OF ALGAE GROWN AT THREE TEMPERATURES ON SWINE MANURE (DRY WEIGHT BASIS)[a]

Temperature	%				ppm					
°C (°F)	N	P	K	Ca	Mg	Zn	Cu	Fe	Na	Mn
23.9 (75)	7.6b	1.0	0.11	0.98	975	2,150a	57a	1,112a	4,650	86
29.4 (85)	7.0b	0.9	0.15	1.09	1,370	2,250a	76b	1,475b	5,975	77
35.0 (95)	6.8b	0.9	0.10	1.04	1,000	4,420b	83b	1,525b	3,650	90

a. Average of eight sample dates and two replications. All means within a column followed by the same letter are not significantly different (P = 0.05) according to DNMRT.

Protein content of algae is important because it is the principal form of nitrogen consumed by the plankton-eating fish. The algae species that dominate will exert the major influence on the suspended solids nitrogen content. Table 8 is a partial listing of algae species that have been observed in the swine-manure-fertilized cultures. Many species have been observed in swine-manure-fertilized cultures grown under a variety of conditions.

Table 9 illustrates the algae dominance observed during June 1977. The greenhouse cultures were all dominated by the blue-green algae during this period. Plankton cultures grown in the open were dominated by the green algae (Scenedesmus) during this same period. Ultraviolet filtration through greenhouse plastic may enhance the growth of blue-green algae.

Table 10 illustrates some values of crude protein content of selected algae populations with identifiable dominant species. Protein content ranged from 37 to 72% on a dry matter basis of collected suspended solids. In general, cultures dominated by green algae during the summer months were found to have higher crude protein content than cultures dominated with blue-green species. During winter months no significant difference in crude protein content was observed in warm water or unheated cultures grown in the open. However, water temperature did appear to influence the dominant species in these tests.

FISH

Culture Selection

The selected culture should include the species and the management factors associated with the successful application of the demonstration

TABLE 8. PHYTOPLANKTON OBSERVED IN SWINE MANURE CULTURES FROM 1975-1978

Chrysophyta	Cyanophyta	Chlorophyta	Euglenophyta
Achnanthes sp.	Arthrospira jenneri	Actinastrum hantzschii	Euglena spp.
Melosira sp.	Arthrospira sp.	Actinastrum sp.	Trachelomonas spp.
Navicula sp.	Chroococcus sp.	Ankistrodesmus falcatus	
Synedra sp.	Cylindrospermum sp.	Chlamydomonas spp.	
	Dactylococcopsis sp.	Chlorella vulgaris	
	Lyngbya sp.	Chodatella sp.	
	Oscillatoria sp. 1	Closterium sp.	
	Oscillatoria sp. 2	Coelastrum sp.	
	Spirulina laxa	Cosmarium sp.	
		Crucigenia sp.	
		Dictyosphaerium pulchellum	
		Golenkinia radiata	
		Micractinium pusillum	
		Oocystis elliptica	
		O. sp.	
		Pandorina morum	
		Scenedesmus arcuatus	
		S. dimorphus	
		S. quadricauda	
		S. spp.	
		Schroederia setigera	
		Selenastrum sp.	
		Spondylosium sp.	
		Tetraedon sp.	
		Tetrastrum sp.	

TABLE 9. SPECIES ABUNDANCE OBSERVED IN ALGAE CULTURES COLLECTED IN JUNE 1977 FROM GREENHOUSE-GROWN CULTURES AND OPEN TANK CULTURES FERTILIZED WITH SWINE MANURE

Source	Temp. °C (°F)	Chlorophyta (Green algae)	%	Cyanophyta (Blue green)	%
Greenhouse	26.7 (80)	Dictyosphaerium	0.1	Anacystis	0.2
		Oocystis	22.4	Lyngbya	19.5
		Scenedesmus	14.6	Oscillatoria	43.3
Greenhouse	29.4 (85)	Oocystis	25.0	Anacystis	0.9
		Scenedesmus	20.2	Oscillatoria	53.9
Greenhouse	35 (95)	Oocystis	3.4	Anacystis	1.3
		Scenedesmus	0.9	Oscillatoria	94.4
Open tanks wall scrapings	26.7 (80)	Oocystis	15.6	Anacystis	0.2
		Scenedesmus	1.1	Lyngbya	2.2
				Oscillatoria	81.0
plankton		Oocystis	6.0	Anacystis	0.2
		Protococcus	0.5		
		Scenedesmus	93.3		

a. Percent based on population counts.

TABLE 10. CRUDE PROTEIN CONTENT OF SUSPENDED SOLIDS OF SELECTED CULTURES OF ALGAE (6.24 x % N)

Dominant algae	Date collected	% Protein (dry wt)
Oocystis (Green)	12-17-76	42
Kirchneriella (Green)	5-24-77	49
Kirchneriella + Scenedesmus (Green)	6-09-77	72
Oscillatoria (Blue Green)	6-09-77	37
Blue Green 35°C (95°F)	11-18-77	42.4
Blue Green 29.4°C (85°F)	11-25-77	43.7
Blue Green 23.9°C (75°F)	11-23-77	47.4

test. However, marketability, fingerling availability, and culture techniques must be determined to assure transfer of technology to the private sector. This section is concerned only with the culture techniques.

Polyculture versus Monoculture--

Polyculture is the growing of two or more fish species together to obtain a desired synergistic effect on total fish production. Polyculture is usually practiced in the United States only in sportfishing in lakes, reservoirs, streams, and managed ponds. Monoculture is the growing of only one fish species in the system and is usually restricted to "fish farming" practices using commercially prepared feeding rations. However, in the case of tilapia both types of production culture have been practiced.

Buck et al. (1976) conducted polyculture yield trials at the Sam A. Parr Fisheries Research Center near Kinmundy, Illinois. A two-section swine house was constructed near the midpoint of a dike which separated two ponds. Ponds were stocked with three species of Chinese carp, common carp, largemouth bass, buffalo fish, and channel catfish. One 0.127-ha (0.31-Ac) pond received the total wastes from five growing pigs (about 39 pigs/ha [16 pigs/Ac] of water area); another 0.121-ha (0.30-Ac) pond received the wastes of eight pigs (66 pigs/ha [27 pigs/Ac]). Two consecutive lots of pigs were fattened during the experiment. Over a period of about 170 days (May to October), the net yields in fish biomass were 2,971 kg/ha (2,650 lb/Ac) in the larger pond and 3,834 kg/ha (3,412 lb/Ac) in the smaller pond.

Total fish production can be increased significantly with the same amount of nutrient input by using the polyculture concept (Dunseth, 1977; Reich, 1975). The use of polyculture concepts at Auburn University resulted in large increases in total fish production without a significant decrease in production of the principal cultured fish--the channel catfish. Nutrient inputs in all treatments were the same, with the polyculture combinations being the principal variable. The polyculture combination of silver carp, tilapia, grass carp, and channel catfish resulted in a net production of 4,576 kg/ha (26 kg/ha [23 lb/Ac]) per day compared with 2,635 kg/ha (14.7 kg/ha [13 lb/Ac]) per day for the channel catfish monoculture.

Moav et al. (1977) evaluated a polyculture of common carp, silver carp, grass carp, and tilapia. Total fish production amounted to 6,282 kg/ha (5,654 lb/Ac) per 126 days (60 kg/ha [54 lb/Ac] per day). High-protein pellets (15% fish meal) were used in this study and fed at a fixed rate. This level of production may be a record for unaerated, static pond culture.

Tilapia can be cultured in both fresh and salt water, making them suitable for inland and coastal culture facilities (Chervinski and Zorn, 1974). Additionally, tilapia are tropical fish and grow well in the warmer water temperatures that are associated with power plants (Graham, 1971). Tilapia reportedly tolerate high levels of ammonia (Stickney et al., 1977), which is an asset in recycling systems where ammonia levels may be unusually high.

Pond culture of tilapia in the United States is undeveloped. Culture constraints to commercial production of tilapia include problems of mass reproduction resulting in stunted populations and the inability of tilapia to survive cool water temperatures. Several methods of controlling reproduction have been evaluated. Hand-sexing of populations to obtain 100% males for stocking is labor intensive and requires fingerlings of 50 g (0.11 lb) or larger for easy sex differentiation (Mires, 1969). Feeding hormone-treated feed to new fry has successfully induced sex reversal, allowing for production of all-male or all-female fish (Anderson and Smitherman, 1978; Clemens and Inslee, 1968; and Guerrero and Haller, 1976). Additionally, hybridization of various tilapia has resulted in production of 90 to 100% male progeny (Lovshin and da Silva, 1975; Pruginin et al., 1975; and Rothbard and Pruginin, 1975). Certain hybrids have exhibited faster growth (Hickling, 1962), increased tolerance to low dissolved oxygen levels, and increased seinability (Dunseth, 1977). Research is being conducted to determine which interspecific crosses produce all-male progeny and which breeding technique produces the most fry (Mires, 1977).

The requirement for water temperatures to be in excess of 13°C (55°F) for tilapia survival may be a significant factor in power plant culture situations. Tilapia have been observed congregating in warmer waters when water temperatures approached lower lethal temperatures (Habel, 1975; and Hauser, 1977). The potential may exist for using this behavioral response for harvesting tilapia from large power plant cooling reservoirs by controlling influent temperatures during cooler seasons of the year.

Commercialization of the tilapia/catfish polyculture operations could become important in the future if hybrid tilapia fingerlings (40 to 50 g [1.4 to 1.8 oz]) could be made available in the spring of the year. It is estimated that there are 22,118 ha (54,633 Ac) of catfish production facilities in the United States (Brown, 1977), providing a potential market for over-wintered tilapia fingerlings. Farms adjacent to power plant sites could use the bio-recycling concept to produce fingerlings which would be overwintered in the thermal effluent. The fingerlings could be marketed the following spring for commerical production in tilapia/catfish polyculture ponds.

Cultured tilapias are being produced commercially in Colorado, Idaho, and Florida as a gourmet food. Social constraints to eating fish reared in waste recycling schemes may not be a problem; a commerical operation in Florida is marketing tilapia reared in cattle waste stabilization lagoons (Fisher, 1976) and other countries throughout the world have marketed such fish with no ill effects (Moav, 1977).

Fertilization Techniques

Table 11 summarizes net production of fish (seasonal and daily average), the percent survival of fish, and the various culture and management techniques tested. Average daily net fish production ranged from less than 1.12 kg/ha-day (1 lb/acre-day) with "low" management inputs to 58 kg/ha-day (52 lb/Ac-day) with "high" management inputs. It is apparent from the wide range in production values attained that the various management techniques tested (i.e., stocking rates, fertilization rates, fertilization techniques,

TABLE 11. FISH PRODUCTION DATA 1976-1979[a]

Year months (days)	Species stocking density No./ha (No./Ac)	Net production kg/ha (lb/Ac)	Daily production kg/ha-day (lb/Ac-day)	Survival (%)	Management techniques
1976	Silver Carp				Fed waste-grown algae at following percentage of body weight
July-Sept. (72)	28,600 (11,579)	6.0 (5.3)	0.09 (0.08)	25	2
		25.0 (22.3)	0.35 (0.31)	49	4
		92.0 (82.1)	1.28 (1.14)	67	16
		167.0 (149)	2.32 (2.07)	79	32
1977 Aug.-Sept. (52)	Silver carp 480,000 (194,332)	317-991 (283-884)	6.1-19.0 (5.4-16.9)	71-88	Polyculture; static water
	Bighead carp 48,000 (19,433)	50-129 (45-115)	1.0-2.5 (0.89-2.2)	88-95	Fed waste-grown algae (2 treatments)
	Tilapia 17,000 (6,882)	190-362 (169-323)	3.6-6.7 (3.2-6.0)	96-100	Direct organic fertilization (2 treatments)
Total	545,000 (220,648)	557-1,482 (497-1,322)	10.7-28.2 (9.54-25.2)	-	
1978 May-Sept.	Silver carp 47,600 (19,271)	790-2,027	7.3-18.6 (6.51-16.6)	39-76	Polyculture static water or flow through
(109)	Bighead carp 3,800 (1,538)				Direct organic fertilization (3 treatments)
	Tilapia, reproduc. 23,800 (9,635)	2,943-4,486 (2,625-4,001)	27.0-41.2 (24.1-36.7)	84-100	
Total	75,200 (30,445)	3,733-6,513 (3,330-5,809)	34.3-51.8 (30.6-46.2)		

(continued)

TABLE 11 (continued)

Year months (days)	Species stocking density No./ha (No./Ac)	Net production kg/ha (lb/Ac)	Daily production kg/ha-day (lb/Ac-day)	Survival (%)	Management techniques
1979 May-Oct (160)	Silver carp 4,800 (1,940)	(-) 300-350 (268-312)	(-) 1.91-2.2 (1.7-2.0)	0-100	Polyculture; static water or flow through
	Tilapia 9,500-28,500 (3,850-11,540)	802-3,926 (715-3,502)	5.0-21.8 (4.5-19.4)	95-100	Direct organic fertilization
Total	14,300-33,300 (5,800-13,500)	502-4,276 (448-3,814)	3.14-24.0 (2.8-21.4)	-	

a. See text for explanation of treatments.

and water management practices [static vs flow-through]) may significantly interact to influence both primary production and average daily production of fish. Therefore, it may be informative to summarize results based on management techniques tested and discuss the practical aspects.

Two methods of organic fertilization were tested to determine optimum fertilization practices for producing filter-feeding fish. During 1976 and 1977, native plankton species were fertilized with liquid swine wastes and cultured independently from the fish. The plankton suspensions were then fed to the fish at predetermined rates.

In the 1976 yield trials, small silver carp fingerlings (3.5 to 4.0 g/each) were fed organically fertilized plankton suspensions daily at rates equivalent to 2, 4, 16, and 32% of the fish's initial stock weight (Maddox et al., 1978).[1] After 72 days of culture (July-September), it was apparent that both relative growth and percent survival of the fish were positively correlated with the feeding rates (Table 12). Relative growth rates (net gain/initial stock weight x 100) ranged from 0.68% per day to 5.3% per day, with the highest growth rate recorded at the 32% level of feeding. Conceivably, higher growth rates could have been attained by feeding at rates greater than the 32% level. Average daily net fish production at the highest feeding rate was equivalent to 2.5 kg/ha-day (2.2 lb/Ac-day). This low level of production may be attributed to the relatively low stocking weight of small fingerlings used during this study, equivalent to 99 kg/ha (88 lb/Ac).

During 1977, a 52-day comparative yield trial was conducted to determine relative differences in fish production as a function of the two fertilization management techniques (Behrends et al., 1980a). Both fertilization of mass-cultured plankton followed by feeding of plankton suspensions to fish and direct fertilization of the fish culture pools were tested, each at two levels of intensity (high vs low). Table 13 summarizes total net fish production and production of component species for the four treatments tested. Relative growth of the three species of fish showed a positive response to increased levels of fertilization, irrespective of the manure-fertilization technique (Figure 7). However, total net production of fish in treatments receiving direct fertilization was significantly greater ($P < 0.01$) than net production in treatments receiving phytoplankton suspensions produced with comparable amounts of manure. Additionally, fish production in high-intensity treatments was greater ($P < 0.05$) than production in low-intensity treatments. The apparent differences in fish yield for the two fertilization management techniques may have resulted from several interacting forces. The continual recirculation-aeration method employed to mass-produce phytoplankton is also an effective waste treatment technique. Such techniques can result in the mechanical stripping of carbon dioxide and ammonia and the precipitation of other essential nutrients (phosphorus, trace metals) required for optimum plankton growth. Limiting nutrient concentrations can reduce photosynthetic rates of phytoplankton (the base of the foodchain) and ultimately fish production. These results suggest that for optimum use of swine manure as an aquatic organic fertilizer

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[1] Feed rates computed on a dry-matter plankton to wet-fish weight basis.

TABLE 12. SILVER CARP GROWTH IN 1976 POOL STUDY (JULY-SEPTEMBER 1976, 72 DAYS)

Feeding level[a] (%) of fish wt	Total Weight (g)	Total Gain (%)	Average Weight[b] (g)	Average Gain (%)	Survival (%)
2	21.3	- 63	2.9	51	25
4	55.3	0	3.8	98	49
16	132.1	+ 128	6.8	254	67
32	220.7	+ 253	9.4	389	79
	$LSD_{0.05}$ = 62.4		$LSD_{0.05}$ = 1.3		
	C.V. = 25.8		C.V. = 2.9		

a. See text for explanation of feed rates.

b. Averages of surviving fish only.

$LSD_{0.05}$ = Least significant difference at the 5% level of probability.
C.V. = Coefficient of variation.

TABLE 13. NET PRODUCTION[a] OF THREE SPECIES OF FISH CULTURED TOGETHER IN SWINE-MANURE-ENRICHED POOLS. AUGUST-SEPTEMBER 1977 YIELD TRIALS, MUSCLE SHOALS, ALABAMA

	Treatments			
Fish species	Low slurry	High slurry	Low manure	High manure
	----------($g/10.5\ m^2$	@ 0.76 m deep)	----------	
Silver carp	317a	545b	739c	991d
Bighead carp	50a	68a	53a	129b
Tilapia	190a	196a	236a	362b
Total net production	557a	809b	1,028c	1,482d

a. Values within a row not followed by the same letter differ significantly at the 0.05 level of probability according to DNMRT. Each value represents the mean of three replications.

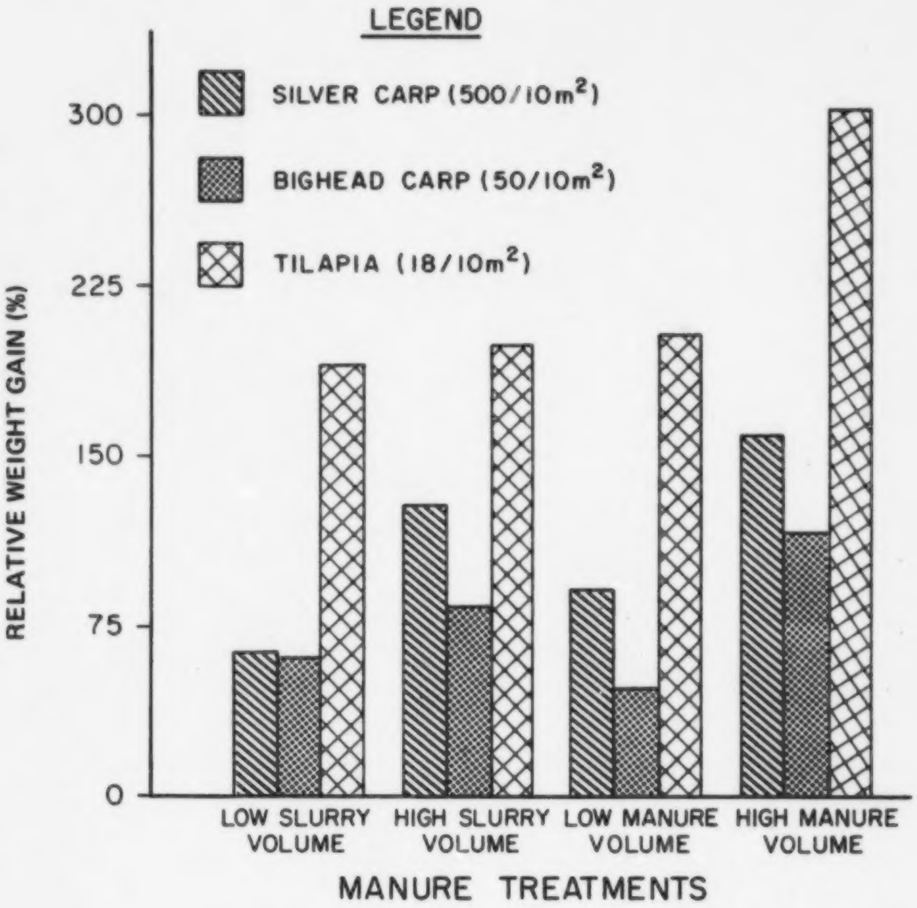

Figure 7. Comparison of the relative weight gain (net gain/initial weight x 100) of silver carp, bighead carp, and tilapia cultured together for 52 days in swine-manure-enriched pools or fed algae slurries grown with swine manure (August-September 1977).

source the manure should be applied directly to the production pond. This technique also precludes the expensive equipment (paddle wheels, pumps) and operating costs associated with the "intensive" plankton production method.

Fertilization and Stocking Interaction

Organic fertilization rates tested during 1977-1979 ranged from 5.8 to 63.8 kg/ha (57.9 lb/Ac) of dry-matter swine manure. Figure 8 illustrates the relationships between fish production and fertility rates for the culture periods 1977, 1978, and 1979. The large interyear differences in fish production at similar fertility rates may be explained on the basis of extreme differences in stocking densities and, to a lesser extent, inherent differences in the fertilizer quality. During 1977, high production resulted from stocking small, nonreproductive fish at high densities (> 200,000 fish/Ac), while the high production in 1978 (Table 14) resulted primarily from tilapia reproduction which occurred due to stocking bisexual populations. In both instances, although high production was realized, the fish were too small to be marketed (28.3 to 113.5 g [1 to 4 oz]). In 1979, hand-sexed populations of all-male tilapia were stocked at rates equivalent to 9,500 to 27,000/ha (3,800 to 11,000/Ac). Stocking all-male fish lessens the competition for food which results from massive recruitment of juvenile tilapia (reproduction) in bisexual stocking situations. Final net fish production (1979) ranged from 3.1 to 24.0 kg/ha-day (2.8 to 21.4 lb/Ac-day) or 502 to 3,833 kg/ha-160 days (448 to 3,420 lb/Ac-160 days).

Figure 9 illustrates relative fish production as a function of stocking density and fertility rate. The low net production observed in the high-fertility, low-stocking-density treatment was attributed to deterioration of water quality. At harvest fish weighed between 84 and 200 g (3 and 7 oz), and the weights were highly correlated with both fertility rate and stocking density.

In static water trials, increasing the fertility rate tended to increase fish production (Figures 8 and 9). At a certain critical point, additional fertilizer inputs resulted in decreased fish production at the lowest stocking density tested. During 1978, increasing the fertility rate from 10.8 to 21.6 kg/ha-day (9.7 to 19.4 lb/Ac-day) of total dry matter resulted in a 51% increase in fish production. However, an additional increase in the fertility rate to 32.4 kg/ha-day (29 lb/Ac-day) resulted in a 35% decrease in fish production when compared to production at the 21.6 kg/ha-day (19.4 lb/Ac-day) treatment. Possibly, accumulation of deleterious chemicals or metabolites contributed to the low production of fish at the high fertility rate.

Water Management (Static versus Flow-Through)

In static water systems, deleterious chemicals or metabolites may accumulate and result in decreased fish production. However, these adverse factors may be reduced considerably by adding fresh water and removing "stagnant water" on a regular basis to dilute the toxic substances. The flow-through concept also provides the potential for adding waste heat. During 1978 and 1979, flow-through systems were evaluated to determine optimum retention periods (time required for complete exchange of water)

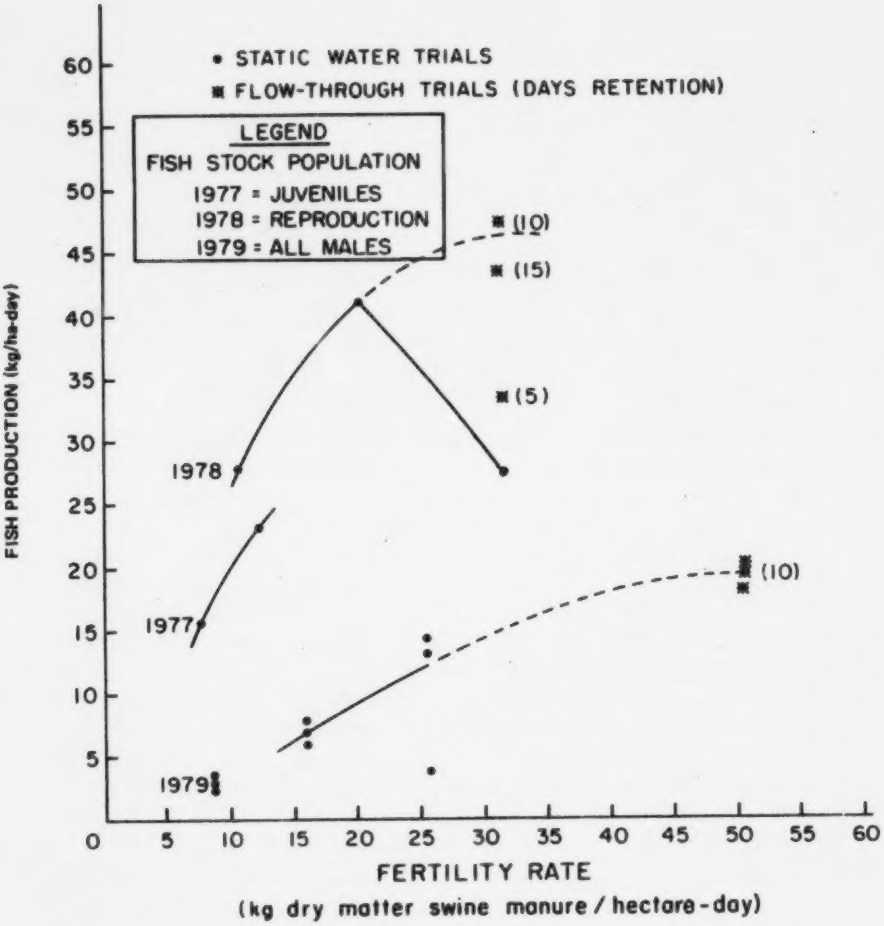

Figure 8. Relationship between organic fertilization rate and fish production as influenced by fish population and water management.

TABLE 14. STANDING CROP AND TOTAL NET PRODUCTION OF SILVER CARP AND TILAPIA CULTURED TOGETHER FOR 109 DAYS (1978) IN STATIC WATER RECEIVING SWINE MANURE AS AN ORGANIC FERTILIZER

Fertility rate (kg dry-matter manure/ha-day)	Standing crop (kg/ha)		Total net product (kg/ha)[b]
	Silver carp	Tilapia[a]	
13.6	993	2,377 (78%)	2,823a
27.3	1,210	3,550 (76%)	4,272b
40.8	1,022	2,258 (83%)	2,791a

a. Tilapia standing crop represents final weight of the original stock plus reproduction. The number in parenthesis represents the percent of the standing crop which was due to reproduction.

b. Means followed by the same letter are not significantly different at the 10% level according to DNMRT.

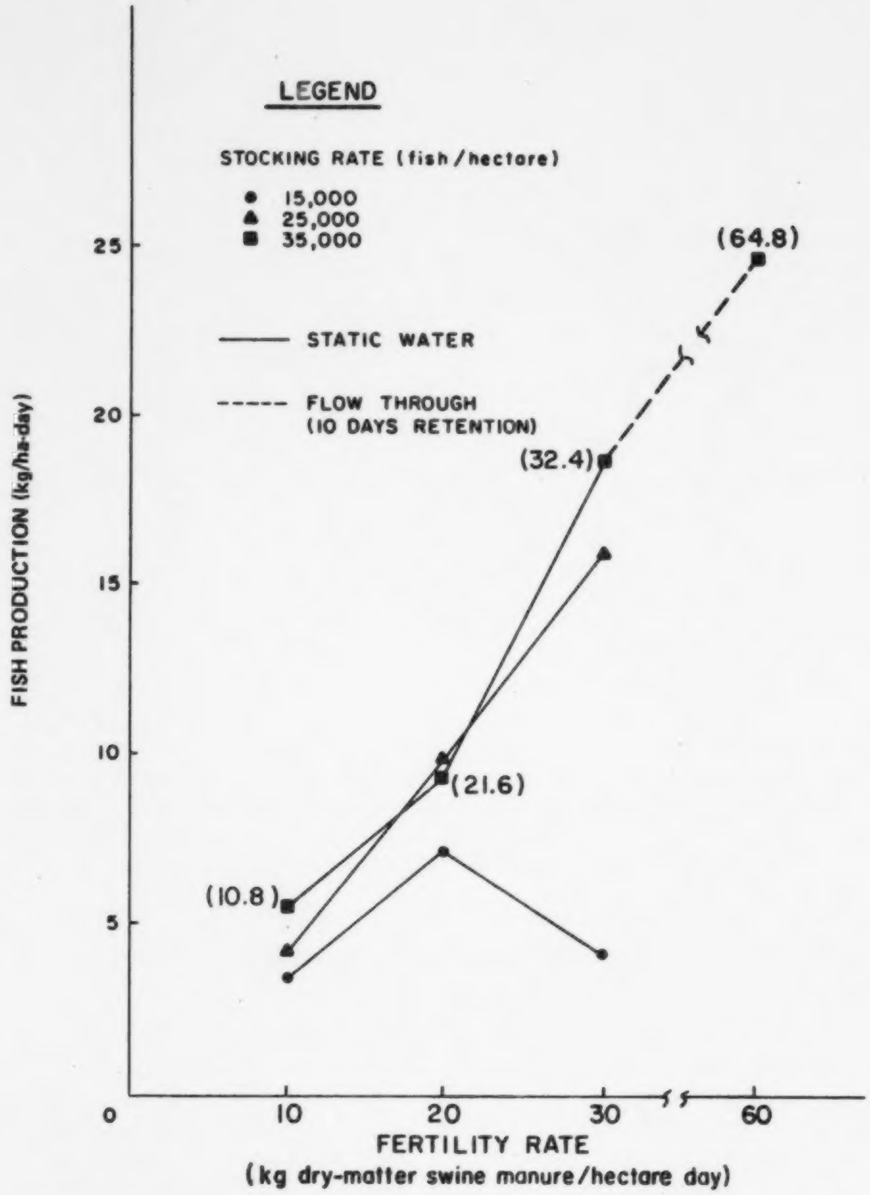

Figure 9. Relationship between organic fertilization rate and fish production as a function of fish stocking rate (1977-1979).

for maximizing production of filter-feeding fish. In 1978, three retention periods (5, 10, and 15 days) were tested and compared with a static water control. Table 15 summarizes standing crops and net production values after 109 days of culture. Relative to the static water control, net fish production increased by 23, 77, and 59% for the 5-, 10-, and 15-day retention periods, respectively. The low fish production for the 5-day retention period may have resulted from too short a period for producing phytoplankton for fish food. Average standing densities of algae (dry matter of suspended solids) were 25, 32, and 37 mg/ℓ for the 5-, 10-, and 15-day retention test, respectively. Poor water quality in the 15-day treatment may have reduced fish growth after a period of time. Initially, this treatment had the highest growth rate.

Based on the results of the 1978 study, a 160-day replicated yield trial was conducted during 1979 to optimize production of market-size fish. The fertility rate in the flow-through treatment (10-day retention period) was increased to 64.7 kg/ha (57.9 lb/Ac) dry-matter manure/Ac-day; this was equivalent to the total wastes of 81 swine averaging 61.4 kg (135 lb) in this test. Net fish production in the flow-through system after 160 days of culture was equivalent to 3,778 kg/ha (3,370 lb/Ac), an increase of 31% over the highest production achieved in the 1979 static water trials. Weight of individual fish harvested from the flow-through system averaged 184 g (0.406 lb).

In situations where useable warm and "flowing" water is available, the flow-through concept can be used to optimize fish production. However, if there are excessive pumping costs associated with flow-through systems, it is necessary to determine whether the enhanced level of fish production is sufficient to offset the additional pumping and capital costs associated with a flow-through system.

Preliminary economic assessments have judged the cost to be too expensive to use heat exchanger technology for enhancing the water temperatures for static fish cultures in large lagoons. Cost effective heat exchangers should be developed for commercial application of flowing water systems. This approach would permit the use of larger quantities of CCW in aquatic systems.

PLANTS

The use of rooted vascular plants to improve (polish) the water quality coming from a fish system is depicted in Figure 1. The amount of plant nutrients removed by conventional irrigation of terrestrial forage or row crops is limited by the water management of the crop as a function of the climate and soil type.

Rooted vascular aquatic plants can remove additional nitrogen and other fertilizer nutrients in the form of a harvestable product. Aquatic plants have higher water requirements as a result of their habitat. Irrigation rate and fertilization rate are linked to the water processing rate for a given waste source and wastewater strength. Therefore, aquatic plants are more suitable when waste water is dilute and cannot be used as a

TABLE 15. STANDING CROP AND TOTAL NET PRODUCTION OF SILVER CARP AND TILAPIA CULTURED TOGETHER FOR 109 DAYS IN STATIC AND FLOWING WATER SYSTEMS

Fertility rate (kg dry matter manure/ha-day)	Water management[a]	Standing crop (kg/ha)		Total net production	
		Silver carp	Tilapia[b]	(kg/ha)	(kg/ha)
40.8	Static	1,022	2,258 (83%)	2,791	25.6
40.8	5-day retention	1,014	2,915 (73%)	3,443	31.6
40.8	10-day retention	1,870	3,545 (65%)	4,924	45.2
40.8	15-day retention	953	3,990 (84%)	4,451	40.8

a. Static water management included replacing water lost to evaporation.

b. Tilapia standing crop represents final weight of original stock plus reproductive recruitment.

conventional source of fertilizer. The choices for aquatic plant species are not great when the plant culture, plant products, and economic factors are considered in the selection process.

Plant Selection

Aquatic plants can be selected from four basic groups based on their growth habits: (1) free-floating on surface, e.g. duckweed; (2) submerged unrooted, e.g. algae; (3) submerged, anchor-rooted, e.g. hydrilla; and (4) emergent, anchor-rooted, e.g. rice. The chosen plant species must exhibit desirable growth in the waste water, have a manageable culture, have a high nutrient requirement, require a long growing season, and have marketable uses to increase its diversity and reduce its economic risk.

These requirements reduce the choices considerably. Commercially cultivated species may have more economic potential; therefore, fewer unknowns are associated with these species than those which are not commercially cultivated and marketed for either feed, food, or fiber. Three species cultivated in the United States seem to meet these requirements: rice, wild rice, and cranberries. All three are anchor-rooted, emergent types. Cultivation of rooted, emergent species offer better opportunity for weed control as a result of soil tillage and water management. However, cultural requirements are based on static water and commercial fertilizer requirements.

Duckweed and water hyacinth have been extensively used to treat various sources of waste water (National Academy of Sciences, 1976). Water hyacinth will not withstand freezing temperatures. Certain duckweed species are cool-season tolerant and will easily withstand the winter temperatures common in the Valley States. However, duckweed uses would be limited to animal feed or composted media for plant growth, and it should be used near its production site.

Water chestnuts (Eleocharis dulcis) appeared to offer many of the required characteristics. Water chestnuts are anchor-rooted, emergent species. They require 150-220 days to mature, need 250 to 300 kg/ha of nitrogen, produce a high starch chestnut, and have a high retail value--$5 to $7/kg ($2 to $3/lb).

Water Chestnut Culture

The Chinese water chestnut (Eleocharis dulcis) is a tropical sedge plant which was first introduced into the United States in the 1940's. The plant is grasslike in appearance and grows to a height of 1.06 to 1.52 m (3.5 to 5.0 ft). A detailed description of this plant can be found in references by Hodge (1956) and Hodge and Bisset (1955).

The fruit is a root crop and is botanically called a "corm" or "tuber." The sizes vary with the variety or plant selection but are generally considered marketable when 2.54 cm (1 in.) or greater. Fertilizer requirements (De Rigo and Winters, 1968), plant disease (Lentz, 1962), weed control (De Rigo, 1964), mechanical harvesting (C. G. Pheil, RJR Foods, Inc. personal communication), problems of storage (De Rigo and Winters, 1976; Newmann et al., 1966), and food processing, including peeling (Leeper and Williams, 1976; and Williams and Leeper, 1977) have been previously studied for commercial development in the United States.

Chinese water chestnuts were suggested as a compatible plant for improving water quality for concurrent production of channel catfish by McCord and Loyacano, 1978. They also suggested that more suitable fertilizer regimes could significantly improve water chestnut production. But, growing water chestnuts in fish ponds did not improve fish yield.

In 1977 six plant introductions were selected and evaluated for their use in the integrated approach to waste recycling. Plant introduction (PI) numbers were: S 2671, 276274, 276263, 276260, 276273, and 106276. A greenhouse experiment was conducted in plastic pots (20 cm deep x 36 cm wide) containing 14.1 kg (6.4 lb) of soil to determine the effect of swine manure on six plant introductions of Chinese water chestnuts (Eleocharis dulcis). Swine manure used in this study was collected from a concrete pit beneath a swine production facility. Equivalent rates of nitrogen were applied (100 mg/ℓ) as manure or inorganic (urea + CSP + K_2O) fertilizer in a single application or as three applications (two-thirds initially plus one-sixth top dressing at monthly intervals). Manure significantly increased the phosphorus (18%), magnesium (7.2%), manganese (16.8%), and iron (290%) in the edible corms. Fresh weight, dry matter, and number of chestnuts were significantly reduced when fertilized with swine manure. Plant introductions, PI 276274 and S 2671, produced the best yield. Water chestnuts were 33.1 and 31.4%, larger than 25 mm in diameter (Table 16), respectively for these two introductions. Manure-fertilized chestnuts flowered later and matured earlier when compared with commercially fertilized chestnuts. Multiple applications of manure had little measureable effect on the water chestnuts. Selection of a Chinese water chestnut introduction for reclamation of livestock waste was made mainly on the basis of chestnut yield and size (Maddox and Kingsley, 1979).

The harvested water chestnut tissue was evaluated for its potential use as a livestock forage for ruminant animals by the Mississippi State University Animal Science Department (James et al., 1979). The ruminant digestibility, corms, and shoot tissue were evaluated for "in vitro" dry matter disappearance (IVDMD), estimated digestible energy (EDE) from a prediction equation, and crude protein (CP) values. IVDMD (83.73%) and EDE (2.9398 kcal/g) values of corms from PI 106274 were higher ($P < 0.05$) than the values of corms from the other plant introductions. There were no differences among the corm IVDMD and EDE values for the other plant introductions. Method of application and source of fertilizer did not influence IVDMD or EDE values of corms. CP values of corms ranged from 6.57 to 8.25%. There were no differences in IVDMD or EDE values of mature shoot tissue from different plant introductions. Source of fertilizer did not influence IVDMD or EDE values of mature shoot tissue (James et al., 1979).

Based on these results, a flowing-water test was conducted in 1978 using fish waste water from a polyculture test where water retention times in the fish ponds were equivalent to 5, 10, and 15 days (Maddox et al., 1979). The experimental design is shown in Figure 10.

TABLE 16. EFFECT OF MANURE AND COMMERCIAL FERTILIZER APPLICATION ON CHINESE WATER CHESTNUT YIELD

	Plant No.	Fresh wt. (g/pot)		% Dry matter		Corms (No./pot)		Size of corms
		Manure[a]	Fertilizer	Manure	Fertilizer	Manure	Fertilizer	(% > 25 mm)
1.	S 2671	282 a	327	28.8 b	33.0	47	57	33.1 ab
2.	PI 276264	299 a	272	28.7 bc	34.5	45	49	31.4 ab
3.	PI 276263	207 bc	271	25.2 c	33.5	32	45	35.3 a
4.	PI 276260	225 ab	317	26.7 bc	33.7	36	56	32.1 ab
5.	PI 276273	157 cf	197	32.0 b	34.5	33	38	23.8 bc
6.	PI 106274	130 f	248	38.5 a	35.2	31	67	8.0 c
	Average	216	272	30.0	34.1	37.3	52	27.3

a. Means within a column and followed by the same letter are not significantly different at the 5% level of probability according to DNMRT.

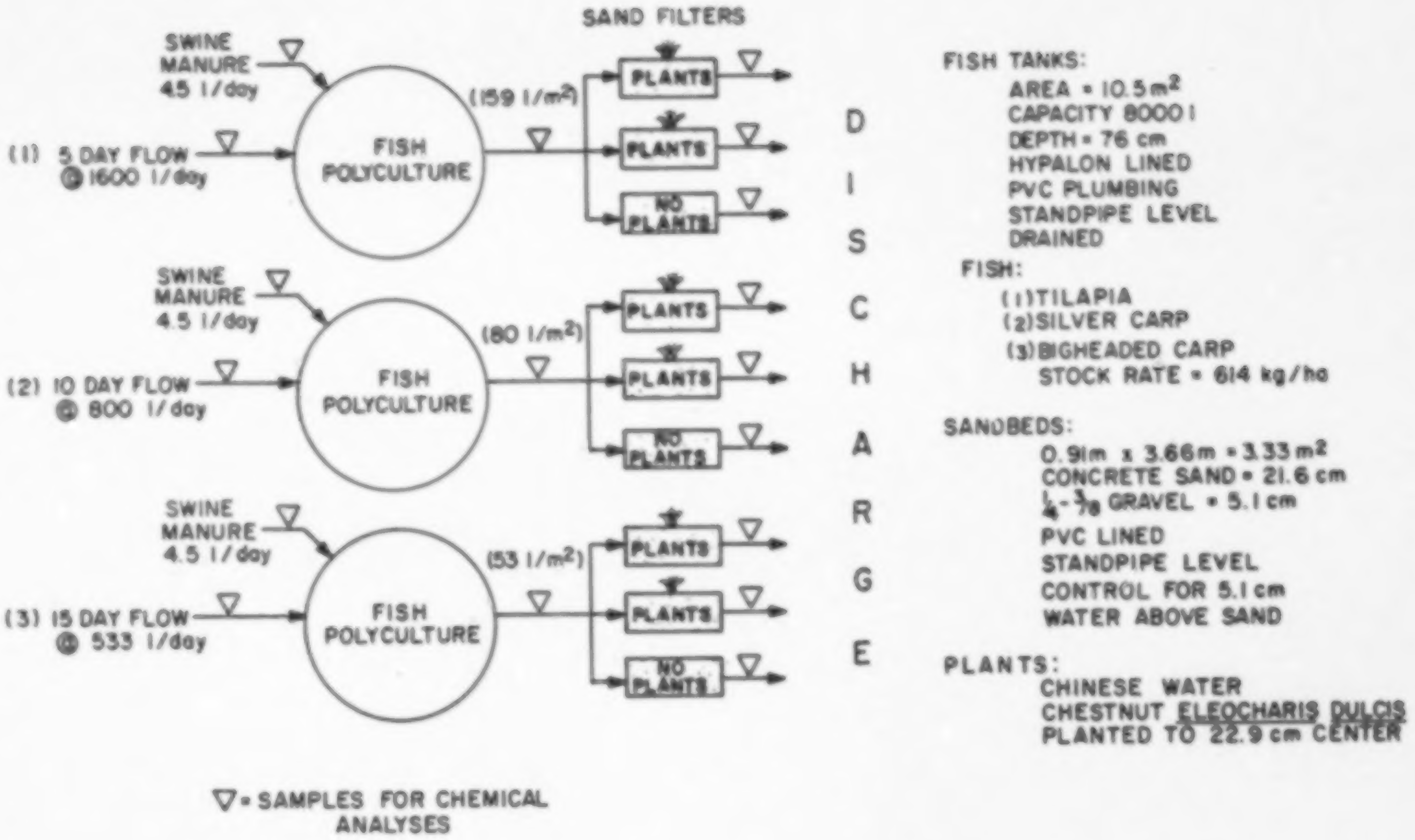

Figure 10. Experimental design for the flowing water production test during the 1978 season (May 23–October 25, 1978).

The recovery of plant nutrients and plant yields are seen in Table 17. The removal rate across the system is shown in Table 18. These results indicated that the integrated approach was capable of effectively removing nitrogen and phosphorous. Nitrogen removal was 86, 95, and 97% and phosphorous removal was 90, 96, and 98% from both the fish and the plant-polishing system. The plants used 15% of the total nitrogen applied to the system and 20.5% of the nitrogen from fish waste in the best results at the high flow rate (159 ℓ/m^2-day).

Phosphorus was used less efficiently than nitrogen and was less predictable at the three irrigation rates tested. The plants used 10.9% of the total phosphorous at the high flow rate and 11.0% of phosphorous from the fish waste. The best removal was observed with the intermediate flow rate (2.0 gal/ft^2-day [80 ℓ/m^2-day]) where 13.6% was used by the plants. Therefore, nearly all of the phosphorous harvested from the system was in the plant tissue. Most of the phosphorous remained in the system as precipitates of calcium and other cations. This factor increased the apparent treatment effectiveness for phosphorous.

The sand filtration beds contain microrganisms that decompose much of the organic fish waste and convert unavailable plant nutrients into available plant fertilizer nutrients. Table 19 indicates the relative treatment effectiveness of the system with sand beds with plants as compared to those without plants. In almost all cases, the plants substantially increased the treatment effectiveness of the system. Total suspended solids and total ammonia nitrogen were greatly reduced by the addition of plants to the system.

Iron and calcium concentrations were increased by adding plants to the system. Presumably, the chemical reducing environment in the sand beds solubilized the oxidized forms of calcium and iron and allowed them to be leached from the bed. This serves to buffer the effluent pH to a more acceptable discharge level. The pH of the discharge was changed from an alkaline level (pH 8-9) to near pH 7 (see Table A-1 and Table A-4).

Effect of Flow Rate--

Based on the 1978 results, a production test in 1979 was conducted to refine the treatment effectiveness of this system by better controlling irrigation on sand filtration beds planted with water chestnuts. The results of the 1979 test better define: (1) the ratio of fish culture area to plant polishing area, (2) the water quality in the effluent, and (3) the predicted plant yields as a function of irrigation rate.

The 1979 test used the effluent from fish cultures with water retention equivalent to 10 days (10 RT). Earlier fish and algae results indicated that 10 RT was better than 5 RT or 15 RT (see fish section). The irrigation rates used were 151, 96, and 57 ℓ/m^2-day (1.4 gal/ft^2-day) which approximates the 1978 irrigation rates of 159, 80, and 53 ℓ/m^2-day.

The water chestnut yields and the hay (foliage) yields are shown in Table 20. These results indicate that the irrigation flow rate was highly significant in determining the yield response and confirms the 1978 results. The flow rate response is not dependent upon the fish wastewater retention

TABLE 17. RECOVERY OF N AND P IN CHINESE WATER CHESTNUT PLANT FRACTIONS - 1978

Flow rate[a] (ℓ/m^2-day)	Plant fraction	Fresh wt. yield (metric tons/ha)	Dry matter (metric tons/ha)	Plant element harvested[b] N kg/ha	N %	P kg/ha	P %
159(5RT)	Chestnuts	38.9	6.8	66.6	4.1	12.2	4.0
	Roots	38.1	4.9	42.6	2.6	5.4	1.8
	Foliage	47.8	11.1	134.0	8.3	15.5	5.1
	Total		22.8	243.2	15.0	33.1	10.9
80(10RT)	Chestnuts	16.3	4.4	32.1	2.0	13.2	4.1
	Roots	14.3	2.4	17.0	1.1	3.4	1.1
	Foliage	27.5	7.2	72.0	4.6	14.4	4.5
	Total		14.0	121.0	7.7	31.0	9.7
53(15RT)	Chestnuts	12.6	2.8	23.5	1.5	9.0	2.4
	Roots	13.1	2.1	15.8	1.0	2.9	0.9
	Foliage	20.9	5.2	63.4	4.2	8.8	2.6
	Total		10.1	102.7	6.7	20.7	5.9

a. Flow rate = irrigation rate from water retention (RT) treatment for fish culture measured in days.

b. Percent of total amount of element removed from the system as measured by difference between influent amd effluent, and assuming no evaporational water losses in the system.

TABLE 18. PARTIAL BUDGET FOR N AND P IN FLOW-THROUGH SYSTEM
(147 DAYS INTO THE 1978 TEST [KG/147 DAY-HA])

Source	Flow rate[a]				Flow rate		
	5RT	10RT	15RT		5RT	10RT	15RT
	N				P		
				INFLUENT			
Manure	1421	1421	1421		332	332	332
H_2O	448	223	149		4	2	1
Total	1869	1644	1570		336	334	333
				EFFLUENT			
Discharged	260	74	46		34	13	8
Removed	1609	1570	1524		302	321	325
% Removal[b]	86	95	97		90	96	98

1. Flow rate = water retention on fish culture system measured in days. Nutrient balances are reported for total system; fish and chestnuts (See Table 17).

2. Percent removal calculated from concentration of discharge and assumes no water evaporational losses.

TABLE 19. COMPARISON OF EFFLUENT FROM SAND FILTRATION BEDS WITH AND WITHOUT WATER CHESTNUTS

Treatment	% Difference[a]		
	5RT[b]	10RT	15RT
Total N	-38	-62	-61
Total NH3^{-N}	-61	-87	-85
Total P	-44	-74	-75
K	-44	-42	-34
TSS	-67	-81	-76
BOD	-27	-67	-85
Algae	-27	-25	0
Fe	+55	+343	+267
Ca	+42	+42	+43

a. Concentration of plant discharge - concentration of discharge without plants ÷ concentration of discharge without plants x 100.
- = decrease with plants
+ = increase with plants

b. RT is the retention time in days; thus, 5RT means a 5-day water retention time in the tanks discharging to the sand beds.

TABLE 20. YIELDS OF WATER CHESTNUTS AND HAY IN RESPONSE TO DAILY IRRIGATION WITH FISH WASTE WATER (1979 COLBERT COUNTY, ALABAMA)

		Water chestnuts (fresh metric tons/ha)		
		Waste water (liters/m^2-day)		
Soil depth (cm)		151	96	57
0 - 7.6	Top	27.0 a	12.4 b	3.7 c
7.6 - 15.2	Mid	11.5 a	8.6 a	12.6 a
15.2 - 22.9	Bottom	1.0 a	2.0 a	2.2 a
Total		39.5	23.0	18.5
R^2 Top = 0.942;	Intercept = -12.565,		Slope = 0.282	
R^2 Total = 0.922;	Intercept = - 5.819,		Slope = 0.351	
Hay (Dry tons/ha)		15.7	5.3	4.3

a. All means within a row followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

time and had a linear prediction equation with a R^2 of greater than 90%, an intercept of -5.819, and a slope of 0.351. Additionally, higher flow rates produced more water chestnuts near the surface of the sand beds and did not significantly influence the yields in the 7.6 to 22.9 cm (3 to 9 in.) depths. Nearly 70% of the water chestnuts were produced in the surface to 7.6-cm (0 to 3-in.) depth at the highest irrigation rate, and this flow rate produced the equivalent of 39.5 metric tons/ha (17.6 ton/Ac).

Flow rate (irrigation rate) onto sand infiltration beds may be limited by certain management criteria rather than plant yield or water quality. The experience in 1979 indicated higher flow rates would probably result in greatly reduced water infiltration rates near the end of the growing season. The effect would be to increase the average depth of standing water above the sand surface. This would require slightly higher dikes to accommodate the additional water. Field tests have shown that water depths greater than 25 cm (10 in.) can be detrimental to the plant yields. Further testing on flow rates and bed design would be required to estimate the influence on yields of flow rates higher than reported in these results.

The ratios of fish to sand bed growing area for the 1978 and 1979 tests are shown in Table 21. In the 1978 tests, area ratios were constant and flow rate on the plant water polishing bed was a function of water retention time through the fish culture. In the 1979 tests, three area ratios were tested (2.29, 1.32, and 0.77), and flow rate was a function of chestnut sand bed growing area. In both years, the highest flow rate gave the highest yields. The availability of plant nutrients was greater in the longer retention time fish effluent. The plant yields from the 1979 tests were greater than 1978 tests. However, these results may have been due to a change in bed design. Bed shape was rectangular in 1978 and square in 1979. A more even growth was evident in the 1979 tests and could have resulted in higher use efficiency of the organic fertilizer. Further testing would be required to determine the nature of this response.

TABLE 21. RATIO OF FISH TO WATER CHESTNUT AREA TESTED IN 1978 AND 1979

Flow rate (ℓ/m^2-day)	Ratio 1978[a]	Ratio 1979[b]
159 & 151	1.05	2.29
96 & 80	1.05	1.32
57 & 53	1.05	0.77

a. 1978 flow rates were a function of fish water retention time.

b. 1979 flow rates were a function of chestnut area.

SECTION VI

PILOT DEMONSTRATIONS

SWINE WASTE TEST

An annual study was conducted from October 26, 1978 to October 12, 1979 at the test facility located at Muscle Shoals, Alabama. The facilities included a confined swine facility, a warm water supply system, a 0.04-ha (0.1 Ac) earthen pond for fish production, and two sand filtration beds planted with water chestnuts in the summer of 1979. During the spring/summer and fall periods of 1979, water used in these studies was pumped from the Tennessee River and preheated to simulate the CCW open-cycle water temperatures of the Browns Ferry Nuclear Power Plant (BFNPP) near Athens, Alabama. During the fall/winter period of 1978, water was heated to a constant 27°C (80.6°F) to maintain tilapia in a temperature-controlled overwintering system (Behrends et al., 1980c).

Facilities

A swine finishing facility was constructed to provide a source of manure. It is a totally insulated structure for 16 pigs ranging from 18.1 kg (40 lb) to 100 kg (220 lb) based on four weights used from feeder pigs to market-ready hogs. The barn measures 6.4 m x 5.8 m (21 ft x 19 ft) and includes the following on a concrete floor: two 1.5 m x 2.5 m (5 ft x 8.3 ft) pens, feed room, one 1.4 m x 1.5 m (4.5 ft x 5 ft) pen to isolate sick animals, and a 4.1 m x 0.1 m (13.5 ft x 2.3) flushing gutter for manure removal. The pens use wood partitions supported by 5.1 cm x 5.1 cm (2 in. x 2 in.) structural tubing set in concrete. A floor slope of 3° in the pen area expedites washdown and cleaning activities. A dosing-siphon mechanism is used with the 4.1 m x 0.7 m (13.5 ft x 2.3 ft) gutter to direct manure from the building. A two-direction splitter box was installed to direct the manure to a 0.04-ha (0.1-Ac) lagoon or to manure handling equipment associated with an anaerobic digester made operational on October 19, 1979.

Ventilation requirements are met by a mechanical fan and natural draft. A fan 45.7 cm x 45.7 cm (18 in. x 18 in.) and screened openings with shutters provide air movement to eliminate high ammonia concentrations in the pen areas.

Potable water is provided by two nipple waterers located in the gutter area. The water feedline is embedded in the concrete with a 1.91 cm (0.75 in.) riser for the animals. This also aids in training the pigs to go to the gutter to excrete wastes.

The dosing-siphon was initially operated on an hourly basis by adjusting the water refilling flow rate. Flush volume was regulated to a constant flush of 94.6 ℓ (25 gal). Later, the flushing mechanism was controlled by a time clock and solenoid valve. This enabled the system to operate on a determined flush volume for a set period during the day. Eight pigs were stocked (four in each pen) and fed free choice with a 16% protein commercial ration. The total wastes, including feces, urine, and uneaten feed, were flushed daily into the pond. The ratio of hogs to pond surface area was equivalent to 200 hogs/ha (80/Ac). Weight of the swine ranged from 18 kg (40 lb) to 114 kg (251 lb) and averaged 59 kg (130 lb). To more closely model management practices of commercial swine producers, four different size classes of swine were reared together during the study to help eliminate large differences in manure volumes that would result from the selling and restocking activities. As individual hogs reached market weight, they were replaced by smaller feeder pigs. Table A-15 and Table A-16 summarize the physical, chemical, and biological characteristics of the swine wastes used in this study.

The diked-earthen pond was equipped with a turndown standpipe for ease of draining. Additionally, an 8-in. diameter PVC sleeve was fitted over a standpipe to force bottom draining, help prevent short circuiting of the warm water influent, and permit level control.

The water used was pumped from the Tennessee River (Wilson Reservoir) through a 54-kW commercial water heater. Beginning October 26, 1978, through February 22, 1979, the incoming river water was preheated to 27°C (80.6°F) and used in a flow-through tilapia overwintering facility prior to being discharged into the pond (Behrends et al., 1980a).

Water retention time in the pond was calculated from average depth (0.6 m [2.0 ft]) and water flow exiting the overwintering facility (950 ℓ/ha-min) (100 gal/Ac-min). During the period March 1 to October 12, 1979, water entering the pond (equivalent to 660 ℓ/ha-min) (70.5 gal/Ac-min) was preheated to simulate once-through cooling water condenser effluent temperatures of the Browns Ferry Nuclear Power Plant (Table 22). Pond water retention time during this culture period was set at 10 days (pond depth = 1 m [3.29 ft]). Calculated retention periods did not account for precipitation, evaporation, flush volumes from the barn, or pond seepage. Preliminary trials conducted during the summer of 1978 indicated that a retention period of 10 days was near optimum for production of filter-feeding fish (Maddox et al., 1979).

The Chinese system of pond stocking (polyculture) was used throughout this study to optimize utilization of available food and pond space (Lin, 1954). Tilapia (*Sarotherodon aurea* and *nilotica*), silver carp (*Hypopthalmicthys molitrix*), bighead carp (*Aristichthys nobilis*), grass carp (*Ctenopharyngodon idellus*), and goldfish (*Carassius auratus*) were stocked in polycultures because of their unique and complementary feeding habits (Moav et al., 1977). Tilapia were chosen as the primary culture fish because of their superior ability to survive and grow well in intensely manured pond cultures (Behrends et al., 1980a) and because of their greater market potential as a food fish (Crawford et al., 1978). Tables 23, 24, and 25 summarize stocking

TABLE 22. BROWNS FERRY NUCLEAR PLANT MONTHLY AVERAGE CONDENSER DISCHARGE TEMPERATURES

Month	Average river temperature °C (°F)	Condenser discharge temperature open cycle °C (°F)
January	6.9 (44.4)	21.3 (70.3)
February	7.4 (45.3)	21.8 (71.2)
March	10.0 (50.0)	24.4 (75.9)
April	16.9 (62.5)	31.3 (88.4)
May	21.5 (70.7)	35.9 (96.6)
June	26.2 (79.2)	40.6 (105.8)
July	28.7 (83.7)	43.1 (109.6)
August	28.8 (83.9)	43.2 (109.8)
September	26.3 (79.3)	40.7 (105.3)
October	21.3 (70.4)	35.7 (96.3)
November	14.7 (58.5)	29.1 (84.4)
December	10.0 (50.0)	24.4 (75.9)

TABLE 23. STOCKING AND HARVEST DATA FOR FIVE SPECIES OF FISH CULTURED TOGETHER FOR 119 DAYS (OCTOBER 26, 1978- FEBRUARY 22, 1979) IN A 0.04-HA (0.1-AC) COOLING LAGOON RECEIVING THE TOTAL WASTES OF EIGHT MARKET HOGS[a]

Fish species[b]	Silver carp	Bighead carp	Grass carp	Goldfish	Tilapia (*nilotica*)	Total
Stocking rate (No./ha)	2,500	100	100	1,250	2,500	6,450 ---
Initial weight (g/fish)	93.4	295	5	83	37	---
Final weight (g/fish)	112	398	20	159	95	---
Growth rate (g/fish-day)	0.16	0.87	0.13	0.63	2.0[b]	---
Mortality (%)[c]	2	0	0	0	100[b]	---
Yield (kg/ha)	40.9	10.3	1.5	95	-92.5	55.2[c]

a. 91 to 100 kg (200 to 220 lb).

b. Total mortality due to inadvertent loss of warm water on December 24, 1978. The 10 fish recovered averaged 95 grams after 29 days of culture.

c. Yield (kg/ha-day) = 55.2/119 = 0.46.

TABLE 24. STOCKING AND HARVEST DATA FOR FIVE SPECIES OF FISH CULTURED TOGETHER FOR 180 DAYS (MARCH 1-AUGUST 27, 1979) IN A 0.04-HA (0.1-AC) COOLING LAGOON RECEIVING THE TOTAL WASTES OF EIGHT MARKET HOGS[a]

Fish species[b]	Silver carp	Bighead carp	Grass carp	Tilapia (*nilotica*) (males)	Tilapia (*aurea*) (males)	Tilapia reproduction	Total
Stocking rate (No./ha)	2,500	250	150	7,500	5,000	---	15,400
Initial weight (g/fish)	75.7	54.1	5.9	45.5	35.9	---	---
Final weight (g/fish)	527	700	800	442	240	35.5	---
Growth rate (g/fish-day)	2.5	4.0[d]	6.1[d]	2.2	2.1	---	---
Mortality (%)[c]	50	100	100	18	0.5	---	---
Yield[e] (kg/ha)	470	- 13.0	- 10	2,377	1,015	2,560	6,400[e]

a. 91 to 100 kg (200 to 220 lb).

b. Silver carp, bighead carp, and Tilapia *nilotica* stocked on March 1, 1979; grass carp stocked on April 2, 1979; and Tilapia *aurea* stocked on May 24, 1979.

c. Complete mortality of bighead carp and grass carp due to oxygen depletion; 50% mortality of silver carp due largely to *Saprolegnia* infection at stocking.

d. Based on data from sample prior to fish kill.

e. Yield (kg/ha-day) = 6,400/180 = 35.6.

TABLE 25. STOCKING AND HARVEST DATA FOR FIVE SPECIES OF FISH CULTURED TOGETHER FOR 33 DAYS (SEPTEMBER 9-OCTOBER 12, 1979) IN A 0.04-HA (0.1-AC) COOLING LAGOON RECEIVING THE TOTAL WASTES OF EIGHT MARKET-SIZE HOGS[a]

Fish species[b]	Silver carp	Bighead carp	Grass carp	Tilapia (*nilotica*) (males)	Tilapia (*aurea*) (males)	Total
Stocking rate (No./ha)	1,250	250	25	275	4,825	6,625
Initial weight (g/fish)	434	322	227	415	235	---
Final weight (g/fish)	582	596.3	430	423	350	---
Net gain (g/fish)	148	274.3	203	8[b]	115	---
Growth rate (g/fish-day)	4.5	8.3	6.2	0.24	3.5	---
Mortality (%)	0	0	0	0	0	---
Yield[c] (kg/ha)	185	68.6	5.1	2.2	555	815.9[c]

a. 91 to 100 kg (200 to 220 lb).

b. No explanation for negligible growth of Tilapia *nilotica*.

c. Yield (kg/ha-day) = 815.9/33 = 24.7.

information for the three culture periods, and the chronological order of these culture periods is shown in Figure 14.

Fish Production

Fish growth rates and production figures for the winter, spring/summer, and fall periods are also summarized in Tables 23, 24, and 25, respectively. Total fish production for the three culture periods was equivalent to 7,270 kg/ha (6,470 lb/Ac). During winter, fish production was minimal (0.5 kg/ha-day [0.44 lb/Ac-day]), compared with average daily production values of 35.6 and 24.7 kg/ha-day (31.6 and 21.9 lb/Ac-day) during the spring/summer and fall periods, respectively. Fish growth during winter months was probably limited by both low water temperatures (range = 8.5 to 20°C [47.3 to 68°F]; mean temperature = 13°C [55.4°F]) and insufficient production of natural food items. Phytoplankton standing crop was low during winter months as evidenced by Secchi disk readings greater than 80 to 90 cm (31.5 to 35.4 in.). However, zooplankton populations (primarily *Daphnia* and various rotifers) were dense during December and January, which may explain the superior growth of the bighead carp and goldfish versus the insignificant growth of the obligate phytoplanktivorous silver carp (Table 3). Compared with summer rates, growth rates of all species were low during March and April when water temperatures averaged 16.4 and 22.4°C (61.5 and 72.3°F), respectively. However, by late May, rates began to accelerate and growth remained strong throughout the spring/summer and into the fall period (Figure 11). Average fish production rates (kg/ha-day) by month were: March, 9.3; April, 26.5; May, 21.5; June, 42.0; July, 22.3; August, 20.7; and September-October, 24.7. Reduced fish growth rates during July and August were attributed to overgrazing, plankton washout via the standpipe, and severe competition for food which was aggravated by excessive tilapia reproduction. However, following pond draining and seine removal of 74% of the fish biomass on October 23, 1979 (including all of the tilapia reproduction), the growth rates of restocked bighead carp, silver carp, and Tilapia *aurea* increased dramatically; subsequent monthly growth rates did not change appreciably. Apparently, partial harvesting benefitted the remaining fish and resulted in the enhanced growth rates of individual fish, but significantly greater production per unit area was not observed during this test period.

Daily fish production (Figure 11) during the 180-day spring/summer culture period averaged 35.6 kg/ha-day (31.7 lb/Ac-day) which is 8% greater than the highest production values reported for heavily fertilized (organic plus inorganic) static water ponds (Moav et al., 1978). Production continued uninterrupted for 180 days at 35.6 kg/ha-day (31.7 lb/Ac-day) while in comparison, a comparable manure fertilized static test was halted after 126 days because of drastically reduced fish growth rates.

The continuous input of fresh water may dilute deleterious metabolites which limit fish production in static water systems. In the previously reported flowing water trials (1978), average daily fish production rates equivalent to 47 kg/ha-day (41.8 lb/Ac-day) were attained in a 147-day culture period. However, the majority of the harvested fish in the previous study were tilapia reproduction and fish were small. In this pilot demonstration, inadvertent stocking of tilapia females (estimated at less than

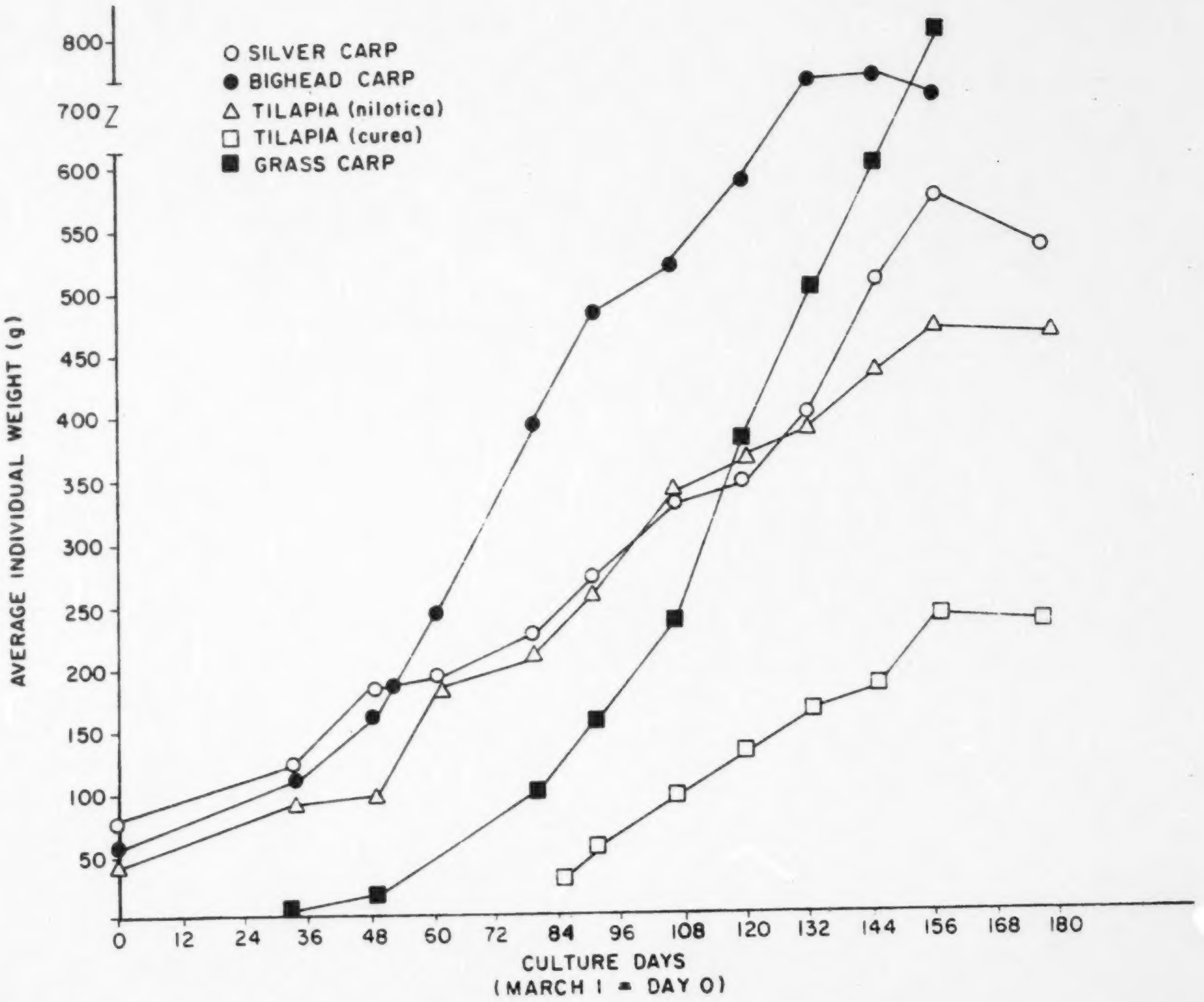

Figure 11. Fish growth during the spring/summer period using swine manure in the pilot demonstration (March 1-August 27, 1979).

one percent of the tilapia population) also resulted in excessive tilapia reproduction (Table 24). Harvested reproduction accounted for 35% of the yearly net production; however, the balance of the harvested fish were within the marketable size range 350 to 530 g (12.3 to 18.7 oz). The problem relating to excessive tilapia reproduction is commonly experienced by fish culturists worldwide and underscores the necessity for developing practical and cost-effective methods of producing monosex stocks of tilapia.

Fish mortality during the winter period was exceptionally low for the carp species, but tilapia experienced a massive kill resulting from their prolonged exposure to water temperatures less than 10 to 12°C (50 to 54°F) (Table 3). During November and December, the tilapia would congregate near the warm water discharge pipe but would swim into colder adjacent waters when disturbed. Temperature differences were as much as 18°C (64.4°F) (27°C inlet vs 9°C adjacent water [80.6 vs 48.2°F]). Shock, resulting from these acute temperature changes, undoubtedly lowered the resistance of the tilapia to various parasites and diseases. Most of the tilapia became infected with the fungus Saprolegnia prior to dying. An accidental loss of heated water on December 24, 1978, resulted in complete mortality of the remaining tilapia. Although the temperature of the warm water influent during winter months was not sufficient to maintain pond water temperatures at levels required for tilapia survival (> 10 to 12°C [50 to 54°F]), it should be noted that the potential exists for using warmer water sources to overwinter tilapia in ponds or in raceways (Behrends et al., 1980c) or to seasonally attract tilapia to warm water influent in ponds and harvest them from pond-extensive culture systems.

During the spring/summer culture period, fish mortality (Table 4) was caused by either fungal infections (Saprolegnia) or by diurnal low dissolved oxygen concentrations. One week after the March 1 stocking, both silver carp and tilapia became infected with Saprolegnia. Silver carp mortality was high (45%) during the first 3 days following infection; however, the fungal growths were brought under control by treating the pond water with formalin (15 mg/ℓ). In August, an early morning oxygen depletion caused mortality of silver, bighead, and grass carp. The deaths were restricted to fish weighing greater than 600 g which included the entire stock of bighead and grass carp. Smaller silver carp and tilapia were stressed and at the surface gulping air but recovered by midmorning (0900) when oxygen production by algal photosynthesis returned DO levels to 1.5 mg/ℓ. Mechanical aeration was used on only one occasion during this study, following a partial die-off of phytoplankton.

During the months of November 1978, to March 1979, the water entering the pond was preheated to 27°C (80.6°F) prior to discharge into the pond to maintain desirable water temperatures in a tilapia overwintering system. Water temperatures decreased rapidly as distance increased from the pond water inlet. At a distance of four to five meters from the inlet, surface water temperatures approached equilibrium conditions. Throughout the winter period, water temperatures in the "heated" pond averaged 13.2°C (56°F) (range = 8 to 21°C [46.4 to 69.8°F]), while water temperatures in an adjacent pond (no water input) ranged from 4 to 18°C (39.2 to 64.4°F) and averaged 8.2°C (46.7°F). Pond cooling effectively reduced the incoming warm water temperature. Conversely, the warm water contributed an additional 5°C (9°F) to pond water temperatures during the winter period. However, it is doubtful that this additional 5°C (9°F) differential enhanced growth of the fish, as warm water culture fish do not grow appreciably at temperatures less than 20°C (68°F).

The monthly water temperatures of the heated pond, control pond, river influent water, and simulated CCW influent during the spring, summer, and fall are illustrated in Figure 12. The cooling action and water dilution of the flow-through pond (10-day retention) reduced warm water effluent temperatures by an average of 11°C (19.8°F) (range = 8.4 to 14.6°C [15.1 to 26.3°F]). During this period, the addition of warm water increased pond temperatures an average of 1.8°C (3.2°F) (range = 0.1 to 3.5°C (0.18 to 6.3°F]) over control pond temperatures.

The benefit of the warm water during transition periods (spring and fall) may have been significant in prolonging the fish culture season. However, during the summer and winter culture periods, the primary benefit of the warm flowing water was the maintenance of water quality for the fish. In static water systems, fish growth and survival were adversely affected when the daily organic fertilization rate was equivalent to the total wastes of 74 market hogs/ha (Stickney and Hesby, 1978). However, by setting pond water retention times at 5 to 10 days, swine density can be increased by a factor of 2.7 (200 pigs/ha [81 pigs/Ac]).

Water Chestnut Production

Two sand filtration beds (93 m^2 each or 1,000 ft^2 each) were constructed in the spring/summer of 1979. These beds were excavated 70 cm deep (24 in.) and sealed with 5.1 cm (2 in.) of clay. Concrete masonry sand was backfilled to 30 cm (12 in.) on top of 5.1-cm (2-in.) PVC pipe for bottom drainage. Slits were cut in the PVC drainage pipe every 70 cm (24 in.) and three sections were placed lengthwise in the beds 0.91 m (3 ft) from the sides and 2.13 m (7 ft) apart. The three drainage pipes were connected at one end of the bed and drained through the 20.3-cm (8-in.) dikes to a level-control standpipe. Water level was maintained at 5.1 to 10.2 cm (2 to 4 in.).

Weather delayed the construction completion date for the sand beds and chestnuts could not be planted until July 30, 1979. This late planting resulted in a short growing season, and plant yields were suboptimal during this test period.

The waste from the summer/fall fish test was applied to the water chestnut beds for 80 days at 200 ℓ/m^2-day. Plants were sample harvested on December 4, 1979 from six plots of 1.35 m^2 (14.5 ft^2) each. Projected yields were 4,374 kg/ha (3,900 lb/Ac) with 48% in the top 7.6 cm (3 in.) and 99% in the top 15.0 cm (6 in.) of the beds. Shoot yield was projected to be 1,555 kg/ha (1,400 lbs/Ac).

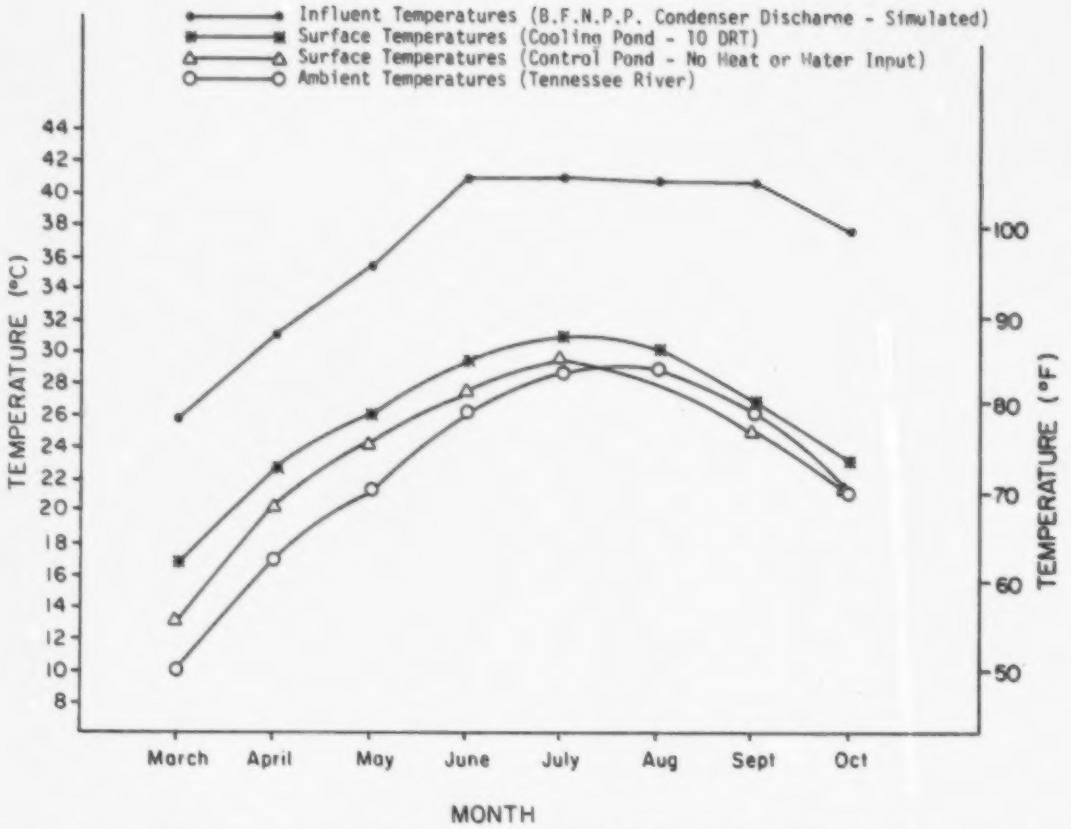

Figure 12. Average monthly water temperatures in the pilot demonstration using swine manure during the spring/summer/fall season (March 1-October 31, 1979).

ANAEROBIC DIGESTER TEST

Facilities

The equipment to process flushing-gutter swine manure was installed into the pilot-demonstration system and put into operation on October 19, 1979. This system was patterned after a system developed at the University of Missouri (Sievers, Fisher, and Fulhage, 1978). The manure-handling equipment permits the simulation of a large-scale system that would use a flushing-gutter system to remove the manure from a confined finishing facility. However, due to the research and development aspect of this study, additional handling equipment had to be installed to allow access to raw waste as well as digester-liquid-waste effluent.

The swine-finishing facility is operated with 12 hogs, but the anaerobic digester receives manure equivalent to only 9 hogs or approximately 75 to 80% of the total available manure.

Separator--

Installation of a separator or splitter box was required to maintain a multiple-use system for the manure collected. A 3:1 split representative of the whole manure collected from a flush sequence in the barn permits the operation of the pilot-scale system and allows continuation of other research and development work.

The separator size is 0.6 m x 1.06 m x 0.38 m (2 ft x 3.5 ft x 1.25 ft) using 1.9-cm (3/4-in.) plywood painted with epoxy paint. A bottom slope of 4° below horizontal allows for manure concentration and easy emptying. A 10.1-cm (4-in.) diameter PVC pipe provides inlet flow from the barn and a 7.62-cm (3-in.) diameter PVC pipe carries the remaining manure (after the mechanical split) to the clarifier. Manure is agitated by using a paddle wheel operated with a Dayton gear motor (Model #2Z797). The stirring action is essential to keep manure particles in suspension while a portion of the 95-ℓ (25-gal) flush is pumped to Storage A (Tait pump model WH5-WH10-submersible waste handling). The remaining manure is allowed to pass to the clarifier when a 7.62-cm (3-in.) motorized control valve is actuated.

Storage A--

A container for collecting 25 to 30% of the raw diluted manure over a 24-hour period was necessary. The 0.91 m x 0.91 x 0.91 m (3 ft x 3 ft x 3 ft) holding tank was constructed with 1.9-cm (3/4-in.) plywood and epoxy coated. Manure is pumped from the separator to Storage A which is capable of holding 760 ℓ (200 gal). This manure is used for other tests that require raw diluted manure.

Clarifier--

The clarifier is a multipurpose structure located downstream from the separator. In the clarifier, the whole manure flushed from the barn is collected, stored, and concentrated to obtain appropriate anaerobic digester loading rates. In order to operate the facility on a daily basis, the clarifier was designed to hold 75% of the total water and manure flushed through the barn. The critical assumption is that the barn would be flushed

12 times/day with a total volume of 1135 ℓ (300 gal). Clarifier volume required was 850 ℓ/day (225 gal/day). From this quantity, the solids are concentrated and pumped into the digester at 9 a.m. daily.

To reduce pumping costs, the clarifier is a sunken concrete structure to permit the use of gravity flow from the separator and the swine barn to it. The clarifier is a rectangular structure with a sloped bottom to a sump area for removal of manure contents. The structure provides sufficient storage and flexible operating alternatives.

When the clarifier is fully loaded, the manure concentration begins. The slurry is allowed to settle for approximately 90 minutes to remove settleable solids from the supernatant. A submersible pump (Zoler 54, 1/4 hp-1-1/4-in. discharge) removes a predetermined volume of the clarified supernatant. This pump was mounted on a screw lift to obtain the necessary sensitivity for adjustment to control the amount of clarified liquid that must be removed daily. The remaining slurry should be 5 to 8% solids concentration. The solids have ranged from 1.9 to 8.1% and averaged 4.6% in the last 6 months (Table A-22). Agitation is applied to resuspend the solids with a paddle wheel similar to that used for the separator. After agitation, a waste-handling pump (Tait Model #WH5-WH10) is energized to pump the contents into the digester tank. The supernatant removed is recombined with digester effluent downstream for R&D activities.

Digester--

The digester containment vessel provides the environment for biochemical degradation of the manure particles. Based on research, the tank was sized using the following criteria: (1) maximum barn occupancy (16 hogs - 40 to 220 lb), (2) digester volume requirement of 0.113 m^3/animal (4 ft^3/animal), (3) volatile solids (VS) loading rate of 4 g VS/ℓ-day (0.25 lb VS/ft^3-day) with a 15-day retention time, and (4) partial volume for methane storage. A 2080-ℓ (550-gal) mild steel fuel storage tank was modified for the digestion tank. The modifications were: (1) additional 5-cm (2-in.) iron nipples welded into the surface of the tank, (2) 2.54-cm (1-in.) iron nipples welded into the surface of the tank, (3) a manhole welded into the top of the tank, and (4) a viewing port welded to the surface of the tank with a 1.27-cm (1/2-in.) plexiglass covering with a rubber gasket. These modifications permit pumping of manure, hot water, and biogas in or out of the tank and for stirring digester contents and viewing interior of the tank.

The amount of manure which was expected to be available was 75% of the total manure excreted by 12 hogs. Total average weight in the barn during a cycle was 735 kg (1,620 lb). The available manure (75%) was expected from 551 kg (1,215 lb) of hogs or the equivalent of 9 hogs. The total solids (TS) available on a daily basis was projected as 0.26 kg/45.5 kg live weight (0.59 lb/100 lb) or 3.1 kg (6.8 lb). Actual measurements gave nearly 5.9 kg (13 lb) of TS in the total waste (Table 26). Suspended solids (SS) comprised 75% of the TS in the raw swine manure fraction, and only 60% of the TS in the settled solids fraction (influent) used for digestion. The total volatile residue available for digester design criteria was estimated to be 1.6 kg (3.5 lb), but it was measured to be 3.0 kg (6.6 lb). Based on the loading rate design of 4 g VS/ℓ-day (0.25 lb VS/ft^3-day).

Based on the measured solids content, the digester required volume is 754 ℓ (200 gal) for the total waste and 565 ℓ (150 gal) for 75% of the waste. At the proposed lower loading rates, the digester volume required would increase if the retention time is held constant. High loading rates would permit smaller digester volumes which would also reduce operating and construction costs.

Biogas Production--

Quantities of biogas produced are based on the amount of destruction of volatile solids where 0.87 m^3/kg (14 ft^3/lb) of biogas is produced per kg volatile solids destroyed (Fisher et al., 1978). The biogas production that was expected from this digester was based on theoretical constants and depends on the percentage destruction of the volatile solids (VS) loaded daily. At a destruction of 60%, gas produced daily would total 0.82 m^3 (29 ft^3) when the operating parameters of pH, alkalinity, volatile acids, etc., and loading rates are controlled for optimum operation. It was estimated that 25% of the available volatile solids would be lost in the manure handling equipment. This loss could be due to bio-decomposition of the solids or physical loss of the solids. The biogas produced daily was assumed to contain 60% methane. The VS destruction averaged only 38% with 0.893 kg (1.96 lb) destroyed daily. The theoretical gas production is 0.776 m^3/day (27.4 ft^3/day) but actual measurements were found to average 0.82 m/day (29 ft^3/day).

The energy produced during anaerobic fermentation has several potential uses. The biogas can be used for fuel to accomplish space heating, heating water, mechanical work, or electrical generation. The density of methane at atmospheric pressure and 0°C (32°F) from the ideal gas law is 0.380 kg/m^3 (0.0237 lb/ft^3). The lower heating value of methane condensation is 50 MJ/kg (21,482 Btu/lb) (Fischer et al., 1978). The heating value of biogas per m^3 is 19 MJ/m^3 (509 Btu/ft^3).

Energy Consumption--

Energy consumed in the anaerobic digestion process can be divided into two categories: (1) electrical and (2) LP-gas. Electrical requirements include those for manure-handling pumps, water-circulating pumps, and controls for manure removal from the barn. A minimal amount of light is needed in the digester building along with some convenience outlets for portable tools, etc. The LP-gas provides the energy required to maintain digester tank temperature. A heat exchange coil is located inside the digester. Hot water (49°C [120°F]) is circulated through the coils. Digester heat is usually provided by the methane produced; however, this was not done in this approach due to the small scale of the system. LP gas is used to maintain the digester at 35°C (95°F). A coiled stainless steel heat exchanger was used to heat the digester contents with hot water from a conventional 190-ℓ (50-gal) residential hot water heater. Approximately one-third of the gas produced will be needed to maintain digester temperatures of 35°C (95°F).

Digester Performance

Table 26 summarizes the physical and chemical characteristics of the waste streams associated with the digester and waste-handling equipment.

TABLE 26. CHEMICAL AND PHYSICAL CHARACTERISTICS OF THE WASTE STREAMS ASSOCIATED WITH THE ANAEROBIC DIGESTER (AVERAGES FOR SIX MONTHS OF OPERATION AND BIWEEKLY SAMPLES)

Variable units	Swine manure	Clarified supernatant	Digester Influent	Digester Effluent	Composite[a]
			mg/ℓ		
BOD	1,800	817	11,485	6,312	1,002
COD	4,400	3,827	25,164	20,500	3,754
SS	3,400	510	27,871	32,250	2,137
TS	4,500	1,500	45,571	35,000	2,100
TVS	2,300	775	36,871	22,850	1,210
STS[b]	33	1	582	657	15
FC[c]	419,500	742,000	733,666	439,000	764,333
TKN	370	282	1,572	1,728	341
$NH_3+NH_4^+$-N	180	165	382	701	185
Organic-N	185	116	1,194	1,020	156
Total-P	124	35	1,855	1,783	77
TOC	2,066	1,900	5,371	5,300	1,914
Ca	290	78	1,631	1,535	115
K	170	125	242	233	128
TA[d]	862	674	1,656	4,405	760
Total acids	44	33	682	696	65
Volatile acids	152	159	535	1,215	133
PH	8.18	7.97	6.73	7.21	7.84
C/N	5.6	6.7	3.4	3.1	5.6
Volume/ 550-kg pigs[e]	1,090 ℓ	1,026 ℓ	64 ℓ	64 ℓ	1,090 ℓ

a. Composite = supernatant + digester effluent

b. ml/ℓ of settleable solids

c. FC = fecal coliforms; colonies/100 mℓ

d. Total alkanlity

e. Liters per 9 pigs equivalent to 550 kg = 0.83 total waste
Total waste = feces + urine + flush water + feed waste + wasted drinking water = 1,312 ℓ/day

Various operating conditions were tested during the first 3 months. These averages do not reflect the observed changes in the waste streams experienced during the first 3 months.

The changes in influent solids can be obtained by comparing influent solids characteristics against digester effluent (Table 26). The influent volume displaces an equal volume out of the digester equal to approximately 63.7 ℓ (16.8 gal). The BOD, COD, TS, and TVS were reduced by 45, 18.5, 23, and 38%, respectively. No nitrogen was lost through the digester, and only 8% was lost through the system by comparing the diluted swine manure with the supernatant + digester effluent fraction. Calcium and phosphorus apparently precipitated in the digester and did not reach an equilibrium during this period. Total acids and volatile acids remained adequate in the digester. Only once in this period and during the first month of operation was the pH and total alkalinity upset by too acidic conditions. A calculated amount of $CaCO_3$ and Na_2CO_3 was used to buffer the pH, and urea was used to fertilize the startup phase.

Methane content of the biogas averaged 50 to 58% with about 0.70 m^3/day (25 ft^3/day). Gas purity and gas production have been below the expected levels of 60% methane and 0.82 m^3/day (29 ft^3/day). It is suspected that this lower gas production was due to short circuiting of solids through the digester tank to give a solids retention time shorter than 15 days. This is evidenced by a higher purity gas 60 to 62% when retention times of 20 to 22 days are used. However, the rate of gas evolution dropped to 430 to 566 ℓ/day (15 to 20 ft^3/day), but the TVS destruction was near 50% or greater during this period.

The TOC:TKN ratio remained relatively unchanged by the removal of carbon from the swine manure, 3.4 before digestion and 3.1 after digestion. The carbon form was changed appreciably, however, as evidenced by the dramatic change in total alkalinity (TA) and the volatile acids in the digester effluent. Presummably these volatile acids would be more easily degraded by the microbial population in the aerobic conditions of a fish production system.

The decanted supernatant was mixed and recombined with the digester effluent and used for the fertilizer material in a demonstration anaerobic digester test similar to the production test and the swine waste demonstration test conducted in 1978 and 1979.

The chemical and physical characteristics of this digester liquid waste are also shown in Table 26. Relative to the whole manure, the BOD, COD, SS, TS, TVS, and STS are reduced in concentration by 44, 15, 37, 53, 47, and 54%, respectively.

The C/N ratio of the manure was 5.6. The settling properties of the manure produced a digester influent with a low C/N ratio (3.4). The high loading rate of 2.33 g VS/ℓ-day has resulted in a highly buffered effluent pH of 7.21. The low rate of destruction for VS (38%) did not appreciably change the total organic carbon potentially available for algae photo-assimilation when digester effluent + supernatant is used as a fertilizer material for the aquatic system. However, the approach can be used to reduce the loading rate for wintertime operation. A reduced loading rate increases gas purity to nearly 60% and VS destruction to nearly 60%. The total carbon fraction can be reduced by 30 to 40% for the winter operation. Tests have indicated that a range of VS destruction of 10 to 60% is possible with the digester unit now being used in this study. C/N ratios of less than 6/1 can result in free ammonia toxicity problems (Sievers and Brune, 1978). Therefore, higher C/N ratios and lower loading rates < 2 g VS/ℓ-day could result in a more unstable food/microrganism (F/M) ratio for the digester. It is not anticipated that high C/N ratios (> 10:1) can or should be attempted with this approach due to the limitations of the system and the potential instability of the digester performance. The digester efficiency could therefore be controlled to produce the maximum fuel gas and the least amount of available carbon during the winter. During the winter period, this may be more desirable due to the increased demand for fuel gas and the decreased demand for organic carbon for the algae system as a result of the combined effects of low sunlight intensities and reduced water temperatures for a fish-algae system. Further tests should be conducted to determine the extent of this approach to digester waste recycling.

Fish Production

A 12-month study was initiated in November 1979 to evaluate simultaneously the aquatic response to effluent from an anaerobic digester and the value of warm water (simulated waste heat) as management tools for enhancing fish growth rates.

The facilities included two 0.01-ha (0.025-Ac) earthen ponds averaging 0.76 to 0.91 m (2.5 to 3.0 ft) deep and two 93 m^2 (1,000 ft^2) each sand filtration beds. Each pond was equipped with independent water delivery and drainage systems. The pond designated "A" received a continuous flow of ambient river water (Tennessee River), while pond "B" received river water which had been heated to simulate the condenser discharge temperatures of the Browns Ferry Nuclear Plant (Table 22). Water management for both ponds involved continuous flow to maintain a 10-day retention time (i.e., a complete exchange of water every 10 days). Water level control and drainage was via turndown standpipes. The standpipes were fitted with plastic sleeves during winter months to force bottom draining, thereby preventing surface skimming of the warmer and less dense incoming river water.

Management of the swine facility was similar to that reported during the 1978-1979 study. However, during the 1980 study, the manure (settled fraction) was pumped daily from a settling pit into an appropriately sized anaerobic digester. An equivalent volume of digested manure was displaced from the digester and recombined with the manure supernatant fraction. This composite (Table 26) effluent was pumped daily to each of the two ponds at a dry matter loading rate equivalent to 76 kg/ha-day (68 lb/Ac-day).

The polyculture system of pond stocking was again used to ensure optimum use of the available food and pond space (Figure 13). Fish were sampled by seining monthly or bimonthly to monitor growth rates. Incoming river water and pond water were monitored for dissolved oxygen concentration and temperature.

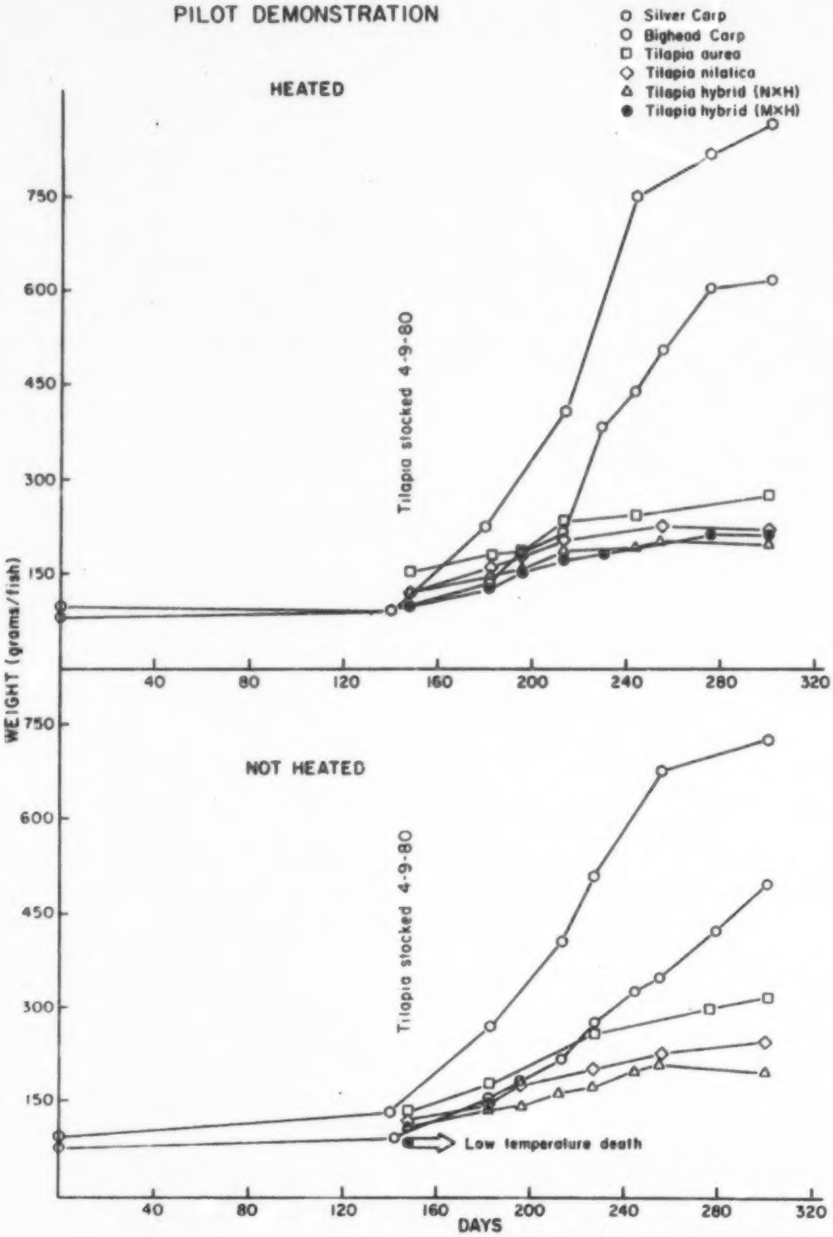

Figure 13. Fish growth rates in the pilot demonstration using anaerobic digester waste as the source of fertilizer (November 14, 1979-September 4, 1980).

Results--

Fish growth rates during winter months were negligible (0.1 to 0.3 g/fish-day) and there did not appear to be any large growth rate advantage in the pond receiving the simulated CCW. Sample data indicate that there may have been reduced growth rates and loss of weight by some species of fish stocked in pond B (Figure 13). The amount of heat entering pond B via the simulated CCW was not sufficient to provide the pond water temperature necessary for significant fish growth. Algae productivity (measured on a computer simulation as a function of daily net oxygen production) was considerably less in both ponds A and B during winter months when compared with summer months. This was partly due to low sunlight intensity and short photoperiods.

An unusually cool spring in 1980 prevented stocking of the tropical tilapia until April 9, 1980. A severe cold front moved into the north Alabama region on April 10 and cooled pond water temperatures from 15 to 16°C (59 to 61°F) down to 10 to 12°C (50 to 54°F). Surface water temperatures in pond A (unheated) remained between 9 to 10°C (48 to 50°F) for a 48-hour period which was critical to tilapia survival. Complete mortality of one cold-intolerant hybrid (*Sarotherodon mossambica* ♀ X *S. hornorum* ♂) was experienced in pond A, while no mortality of this hybrid was experienced in pond B (heated pond). Although the average surface water temperature in pond B was only 1 to 2°C (1.8 to 3.6°F) warmer than surface water in pond A during this period, a small sanctuary near the warm water inlet (20 to 22°C) (68 to 72°F) was adequate for tilapia survival.

Apparent fish growth rates from seined samples in ponds A and B were similar during the spring and early summer culture period. Table 28 summarizes the growth of the various fish species stocked in ponds A and B for the culture period April-July 1980. Theoretically, the fish in the pond receiving the warm water (pond B) should have experienced superior growth because of better temperature regimes. However, differential fish mortality of certain species stocked into the two ponds resulted in density-dependent fish growth factors which had the effect of masking positive effects that the warm water may have had on total fish production. Based on seine sample data, mortality figures and culture duration (April through July 1980), net fish production in ponds A and B was equivalent to 12 and 18 kg/ha-day (11 and 16 lb/Ac-day), respectively. Some difference in production between ponds A and B resulted from large differences in mortality, especially in regard to the early spring kill of tilapia in the unheated pond.

The relative value of the digester effluent as an organic fertilizer compared well with previous results with swine waste. The relative value of the digester effluent as an organic fertilizer can be evaluated by its ability to produce algae and fish. Although no comparative yield trials were conducted in the same year, the fish growth can be compared from results obtained during 1979 and 1980. The fertilizer used in 1979 was raw diluted swine manure in the demonstration, and digester effluent was used as the only source of fertilizer in 1980. Fish growth rates in 1979 achieved 35 kg/ha-day (31 lb/Ac-day), while in 1980 the growth rate was approximately one-half this rate at 18 kg/ha-day (16 lb/Ac-day).

Part of the inter-year production differences may be attributed to the difference in the fertilizer characteristics of diluted raw manure and digester liquid effluent. In fertile aquatic production systems where sufficient nitrogen and phosphorus are available for algal growth, the limiting factor to primary and secondary production is often the availability of a photosynthetic carbon source (King, 1976). The process of anaerobic digestion to produce biogas can remove up to 60% of the VS. When the anaerobic digester removed 0.89 kg (1.96 lb) of VS/day, approximately 50% may be elemental carbon and can be removed (personal communication A. G. Hashimoto, U.S. Meat Animal Research Center, Agricultural Research, USDA, Clay Center, Nebraska). Therefore, with 2.61 kg (4.75 lb) of TS destroyed in the system and approximately 0.45 kg (1 lb) of carbon removed, it is estimated that 17% of the total solids lost in the system would be elemental carbon. Further studies are needed to determine if this amount of carbon is a significant loss to the available carbon for potential use for photoassimilation. Indeed, additional study is needed to determine the amount of available carbon that can be provided by the addition of either swine waste or digester waste to a phototrophic system in an aquatic medium.

Duckweed Production

Lemna minor was selected from a local growing stock and seeded onto the sand beds after the chestnut harvest in November. An earlier test by R. A. Stanley had indicated a growth of 37 g/m^2-wk (14 oz/ft^2-wk) was possible with duckweed when fertilized with swine lagoon waste water under greenhouse conditions (Stanley and Madewell, 1975).

Standing crops in the spring harvest were as high as 7 kg/m^2 (1.4 lb/ft^2) wet weight or 644 g/m^2 (0.132 lb/ft^2) dry weight. These yields result in a projected yield of 6.4 metric ton/ha (dry weight 3.0 ton/Ac) of duckweed to be harvested in the spring. The crude protein analysis ranged from 21 to 32% on a dry basis.

Duckweed is easy to harvest with flotation equipment or skimming techniques. However, it averaged nearly 91% water. With this much moisture, the tissue is difficult to dry and store. Solar dryers may be useful in solving this problem.

Duckweed growth rate during November 1979 was measured at 16.7 g/m^2-day (0.0035 lb/ft^2-day). This growth rate compares favorably with plants used as winter cover crops such as rye grass and fescue. The crop could be expected to attract waterfowl if a sufficient production area was located in a flyway of migratory waterfowl.

Water Chestnut Production

Water chestnuts were purposely not completely harvested from the sand filtration beds from the previous swine waste test. The water chestnuts sprouted in early April and covered the area with a dense stand of foliage. Soil infiltration plus evaporational losses of water from the warmer simulated waste-heated pond were significantly greater than from the unheated pond. Additionally, the soil infiltration rate of water has been higher from the sand filtration bed receiving the simulated waste-heated water. Lateral water movement from this sand bed is also greater than the sand bed receiving the unheated water. Difficulty in maintaining sufficient water supply to the beds resulted in a weed competition with chestnuts.

Little difference was observed in the water quality of the fish effluent being applied to the two beds from the unheated and heated simulation fish test. Differential growth is not anticipated due to the similarities of the fertilizer characteristics of the water quality test during this short test period. The water chestnut growth is better in the unheated test, but is attributed to the physical differences of the two beds that reduced the available nutrients to the heated wastewater system relative to the unheated test system. More definitive results from this test will be available in the future.

SECTION VII

WATER QUALITY

Water quality data were taken for the process effluents in 1978, 1979, and 1980. The 1978 data were previously discussed in the specific sections on fish and plant production trials and reported in Maddox et al. (1979). The trials in the 1979/1980 season are discussed as two sets of water quality monitoring: (1) production test periods (Figure 14) and (2) pilot-demonstration test periods (Figure 15). Measurements on water quality effluents, manure composition, ground water supply, river water supply, and anaerobic digester are found in the appendix.

PRODUCTION TEST PERIODS

Production test periods and significant dates are shown in chronological order in Figure 14. These tests began on May 18, 1979 and continued to day 340 on April 22, 1980. This test was conducted in hypalon-lined tanks (8,000 liters), and fish-water retention rates were set at 10% exchange per day (RT = 10). Fish were grown in polyculture for 158 days (harvested on October 23, 1979) and received manure daily equivalent to 266 hogs/ha (108 hogs/Ac) weighing an average of 61.4 kg (135 lb). The tilapia were removed and a polyculture of silver carp and bighead carp was restocked.

The fish wastewater effluent was applied to water chestnut sand filtration beds during both fish test periods, and three rates of irrigation equivalent to 57, 96, and 151 ℓ/m^2-day were used in this study. Sand filtration beds were lined with two layers of 6-mil greenhouse clear plastic, equipped with bottom drain and level control standpipes, and filled with 30.5 cm (12 in.) of masonary sand. Chinese water chestnuts were grown in a hot house for 59 days prior to planting in the water quality test beds on May 11, 1979 and were harvested on December 12, 1979, 208 days into the test period. These plants grew 188 days in the test until a killing frost occurred on October 14, 1979. This test period is referred to as the spring/summer/fall season preharvest period of May 18-December 12, 1979 (Figure 14). The sample dates for water quality tests are shown in Table A-26. Characteristics that were studied and seasonal averages for the spring/summer/fall season are compared in Table 27 for the effluents from the fish and water chestnut production systems. For most parameters measured, the treatment effectiveness can be seen as a change in the concentration in water chestnut effluent relative to the fish effluent or relative to the water source used in the study.

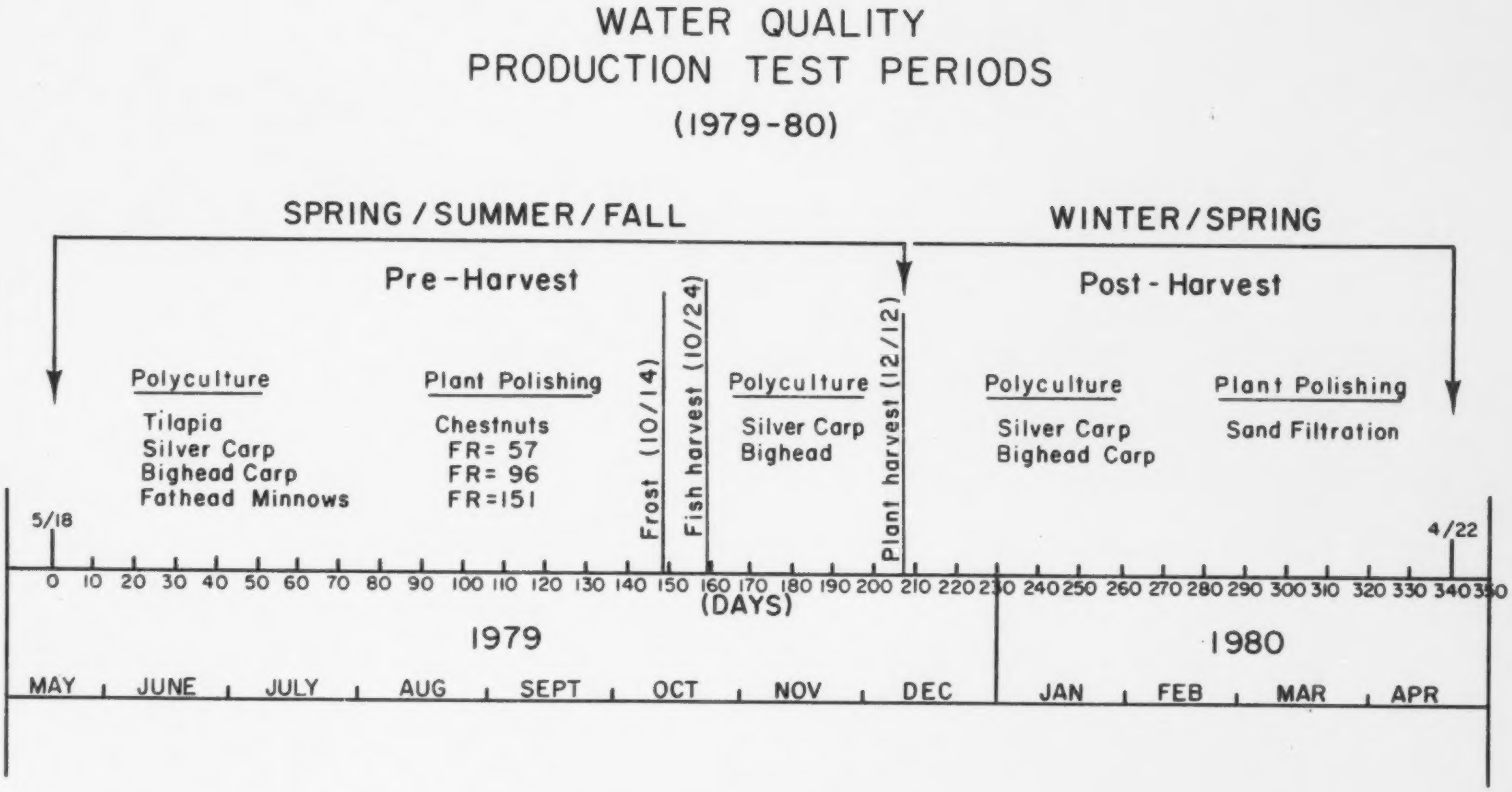

Figure 14. Chronological order of culture events in fish tanks and water chestnut sand filtration beds for flow rate production test during the 1979-1980 season.

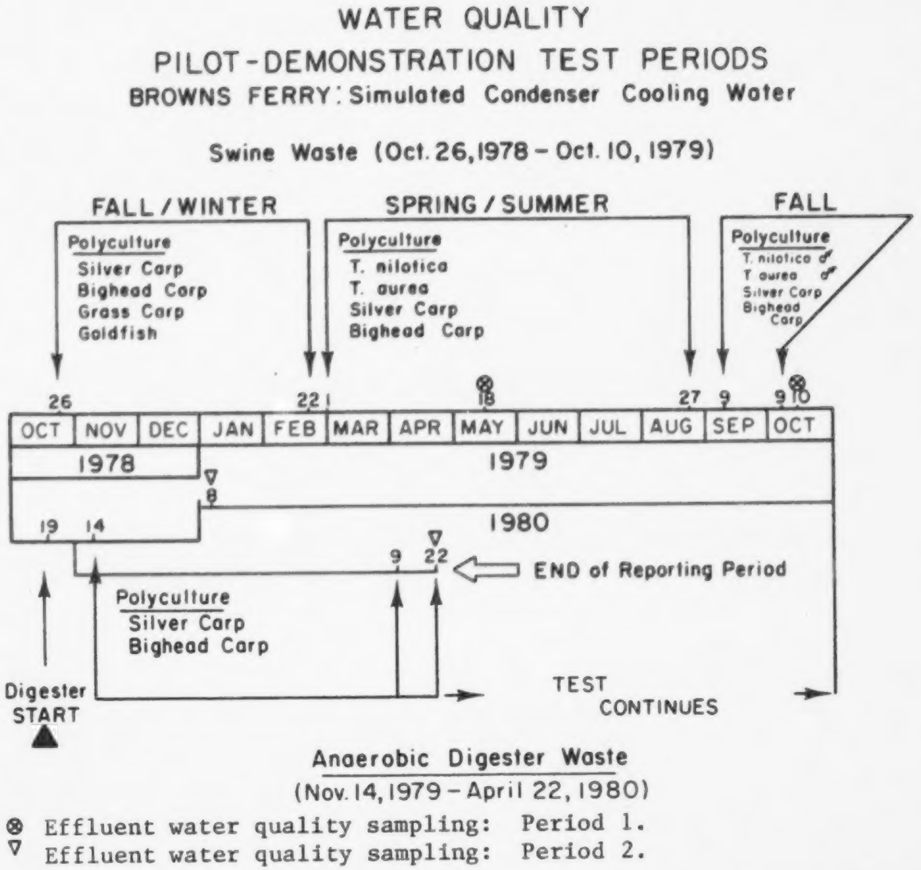

Figure 15. Chronological order of culture periods in the pilot demonstrations using swine manure and anaerobic digester liquid waste.

TABLE 27. SEASONAL AVERAGES OF EFFLUENT WATER QUALITY FROM PRODUCTION TEST WITH FISH AND WATER CHESTNUTS (mg/ℓ)

[Spring/Summer/Fall] May-December 1979

Effluent variable[a]	Water source[b]	Fish	Water chestnuts Irrigation rate (ℓ/m^2-day)		
			151	96	57
BOD	6.92	18.8	5.08	4.66	3.80
COD	5.00	79.7	25.6	25.2	23.5
SS	2.38	53.3	11.9	8.37	8.97
TS	453	581	532	544	514
STS	0.20	0.61	0.20	0.20	0.20
TKN	0.96	3.03	1.13	1.03	0.77
$NH_3+NH_4^+$	0.03	0.44	0.41	0.40	0.16
ORGN	0.89	2.57	0.72	0.76	0.59
NO	1.81	0.25	0.16	0.08	0.06
TOTP	0.25	1.30	0.61	0.44	0.32
TOC	22.2	38.0	19.3	17.8	17.8
TOTC	25.0	49.5	37.0	32.9	34.0
TC[c]	82,280	300,086	147,177	291,522	214,038
FC[c]	1,733	5,890	450	650	750
Ca	49.5	47.1	51.6	49.6	48.8
Mg	3.85	4.50	4.44	4.37	4.27
Na	109	119	120	117	115
K	5.46	8.35	7.45	7.23	6.66
Fe[d]	122	267	1,383	1,360	1,537
Cu[d]	11.8	14.1	13.1	11.7	16.5
Zn[d]	149	119	33	19	43
Pb[d]	10	10	10	10	10
As[d]	2.0	2.1	2.3	2.5	2.6
Mn[d]	13.3	51.0	49.7	45.5	50.0
DO	5.92	13.0	7.83	8.25	9.34
DOS	.	.	1.74	1.69	1.26
HARD	135	142	140	141	134
pH	7.21	8.51	6.87	6.81	6.82
T	20.3	26.4	22.8	22.8	22.7
TA	88.7	170	107	107	103
PA	.	12.3	0.39	0.01	0.17
CB[e]	.	968	939	937	921
CP[e]	.	.	926	923	910
ALGAE[f]	.	991,242	615,696	550,000	492,812
TP	.	.	22	22	22

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a. See List of Abbreviations and Symbols, page xi.

b. Ground water supply

c. Colonies/100 mℓ

d. µg/ℓ

e. µhmos/cm

f. Cells/mℓ

During the spring/summer/fall season, the seasonal averages of effluent quality were mostly improved relative to the ground water source for biological oxygen demand (BOD), organic-N (Orgn-N), nitrite + nitrate-N (NO), total organic carbon (TOC), fecal coliforms (FC), Mg, Na, and Zn. The total solids (TS) were increased in the system, approximately 20% of which was due to an increase in dissolved solids. The water hardness was not appreciably changed, but total alkalinity was increased approximately 20%. Upon closer examination, it can be seen that Mg may be the principal cause of the alkalinity change as a result of a 92% increase for the season relative to the water source. Ca was used in large amounts and was only slightly increased, while Na, K, and total carbon (TOTC) were increased by 8, 1.6, and 9.6%, respectively.

No differences were observed in the final fish tank effluent for Ca, Mg, Na, Cu, Pb, Mn, and hardness. However, Ca showed a trend toward increasing in concentration from the fish effluent to the water chestnut effluent, and Fe was significantly increased. This is similar to the results obtained in 1978. This is partially explained by the low DO in the water chestnut effluent, which results in a solublization of Fe and Ca from the insoluble oxidized forms into the soluble reduced forms.

Water quality of power plant condenser cooling water (CCW) would be unique to the site and type of power plant. TVA has stipulated a few potential constraints for the use of CCW. One such stipulation is return of the waste-heated water after use elsewhere to a closed-cycle plant at the same or higher water quality as received. It is of interest to compare effluent water quality of the aquaculture/agriculture system tested with the water quality of the water source (Table 27 and Table A-17) for the spring/summer/fall season and the winter/spring season (Table 28 and Table A-18). Evaporation losses are inevitable in this system, and evapotranspirational losses from growing plants can be greater than simple evaporational losses. In this test, evaporation losses are replaced by water level controls in the fish tanks.

The period from December 13, 1979 to April 22, 1980 is referred to as the winter/spring season or post-harvest time on the plant-polishing effluent treatment. During this period, silver carp and bighead carp were grown, and the same flow rates were applied to the sand filtration beds for wastewater treatment. The plant sand beds were cultivated to simulate a mechanical harvesting practice. The beds were allowed to heal for 10 days and irrigation of fish waste water was resumed. No plants were seeded into the beds in order to test the magnitude of the seasonal changes that must be dealt with to minimize the winter pollution potential during the winter/spring season.

The winter/spring seasonal averages of selected water quality variables in the effluent are given in Table 28. Most variables tested were observed to have higher values in the effluent water than in the water source (ground water). TS, Ca, and temperature were unchanged by the system. These data indicate that secondary wastewater treatment standards could be achieved during the winter period. BOD and SS averaged less than 20 mg/ℓ, and only occasionally were values observed to be greater than 30 mg/ℓ during this period. Fecal coliforms (FC) averaged approximately 20% higher in the effluent relative to the water supply during the winter but lower than the

TABLE 28. SEASONAL AVERAGES OF EFFLUENT WATER QUALITY FROM PRODUCTION TEST WITH FISH AND WATER CHESTNUTS (mg/ℓ)

[Winter/Spring] January-April 1980

Effluent variable	Water source[a]	Fish	Sand bed filtration Irrigation rate (ℓ/m^2-day) 151	96	57
BOD	1.45	22.2	19.7	16.5	13.2
COD	7.00	61.7	59.7	53.2	47.1
SS	1.57	30.0	13.0	10.4	13.3
TS	380	386	362	379	359
FC[b]	357	2,461	1,062	433	561
TKN	0.09	3.29	3.53	3.42	2.70
NH_3+NH_4^+-N	0.02	0.73	1.92	1.83	1.28
ORGN	0.07	2.56	1.75	1.59	1.37
TOTP	0.01	1.31	1.41	1.57	1.08
TOC	61.3	171	113	95.7	122
Ca	39.4	39.1	41.1	42.9	40.5
K	4.92	7.26	8.01	8.21	7.74
pH	7.01	8.36	7.27	7.47	7.54
T(°C)	8.5	8.6	8.6	8.6	8.6

a. Ground water was used in this test (see Table A-18).

b. Colonies/100 mℓ

water supply during the spring/summer/fall season. However, analytical sensitivity to fecal coliforms analyses was not greater than 100 colonies/100 mℓ during this period, and many values were reported as such. Total ammonia-N (NH_3 + NH_4^+-N) averaged less than 2 mg/ℓ. Due to the low temperature (8.6°C) and the pH values of less than 7.5, the free unionized ammonia averaged less than the recommended maximum level for permissible discharge criteria; 0.02 mg/ℓ-NH_3.

Dramatic reductions in effluent BOD, COD, SS, and TKN were observed when the fish were removed on day 158. The fish pools must be drained to obtain access to the fish by seining. The resulting discharge of accumulated organic constituents could be temporarily polluting to the receiving stream. Continued addition of swine manure into the fish pools after refilling resulted in an accumulative increase of these water quality constituents during the winter period.

Based on these results, there appears to be much justification for the water quality improvement from plant polishing. However, the amount of water treatment improvement achieved by the lower irrigation rates does not appear to be justified on the basis of reduced yield. Water chestnut yields were reduced by 42 and 53% (Table 20) relative to the highest irrigation rate while BOD, SS, and NH_4^+ + NH_3-N were only reduced by 25, 30, and

61% in the effluent concentrations. These reductions in effluent concentration can be compared with the irrigation rates. The low and medium irrigation rates were 36 and 62% of the highest rate tested. The reduction in irrigation rate did not result in a proportional improvement in water quality.

PILOT DEMONSTRATION

Swine Waste Test

The pilot demonstration test was divided into three parts consisting of (1) fall/winter, (2) spring/summer, and (3) fall. Water quality measurements were taken during the spring/summer and fall test periods, covering the period of May 18, 1979 through October 10, 1979 (Figure 15). During this time, selected water quality parameters were measured for fish wastewater effluents. The seasonal averages of the river water source, fish effluents, and water chestnut effluents are compared in Table 29. During this test period, swine manure was added daily in an amount that was equivalent to the waste from 12,300 kg of hogs applied to one hectare of water (11,000 lb/Ac) in the test pond which was 0.04 ha (0.1 Ac) in size.

During the earlier period (fall/winter, Figure 15) simulated waste-heated water was passed through an overwintering system where tilapia were grown in flowing water termperatures near the optimum for tilapia, 29.4^{o}C to 32.2^{o}C (85^{o}F to 90^{o}F). The effluent water quality was not monitored from this system and was combined with the swine waste in the "growout" pond during the fall/winter period. No values are reported for this effluent water quality during this period of testing, but total solids from this system were probably less than 10% of the total solids applied to the swine waste system.

The water quality parameters measured during the study period were generally quite comparable to those observed in the production test conducted in the small units (Table 27 and Table 29). The treatment effectiveness appears to be better than predicted from the production test. This can be partially explained by the ion-exchange capacity of the soil in the earthen pond and the clay matrix lining the pilot-demonstration water chestnut beds. Water was irrigated onto the water chestnut beds at a rate equal to 100 ℓ/m^2-day. This irrigation rate was chosen as an intermediate to the three rates tested in the production test (see Table 27).

The most striking difference in the comparison of the pilot-demonstration test and the production test is the water source. The river water was significantly lower in total solids (TS) and total alkalinity (TA) than the ground water supply. The ground water supply is considerably higher in Ca, Na, and K than the river water used in this pilot demonstration. This factor, in addition to the added benefit to soil-water ion-exchange capacity, helps to improve the TS content and other water quality characteristics in the final effluent. The TS content of the effluent averaged nearly 30% less than the influent river water. However, the total alkalinity was nearly 60% higher in the effluent relative to the river water, and the equivalent $CaCO_3$ hardness was nearly 25% higher.

TABLE 29. EFFLUENT WATER QUALITY FROM SWINE WASTE FERTILIZED PILOT DEMONSTRATION TEST [MAY-OCTOBER 1979] AND WATER SOURCE USED IN THE TEST (mg/ℓ)

	Fish lagoon			River water[a]
Variable	Bottom	Surface	Water chestnut	influent
BOD	12.6	14.6	4.4	5.4
COD	46.0	55.6	14.0	5.1
SS	56.0	35.5	9.0	3.0
TS	357	260	138	196
TKN	3.43	3.17	0.53	0.67
$NH_3+NH_4^+$-N	1.75	1.53	0.41	0.05
ORGN	1.66	1.65	0.56	0.62
NO	0.27	0.20	0.01	0.31
TOTP	2.02	0.79	0.20	0.19
TOC	28.6	29.6	-	19.1
TOTC	39.6	42.8	-	20.3
TC[b]	52,500	336,911	27,750	102,000
FC[b]	1,044	17,114	< 10	4,135
Ca	25.6	27.1	-	20.8
Mg	4.26	4.53	-	3.79
Na	61.3	33.7	-	24.9
K	6.38	6.73	-	1.70
Fe[c]	1,356	1,122	-	181
Cu[c]	17.5	14.4	-	12.2
Zn[c]	76.0	69.0	-	29.0
Pb[c]	10.0	10.0	-	10.0
As[c]	4.22	4.21	-	2.00
Mn[c]	81.0	220	-	30.0
DO	-	3.27	0.4	8.07
HARD	81	86	82	66.0
pH	7.28	7.51	6.89	7.57
T(°C)	27.8	28.0	18.4	18.5
TA	77.0	74.5	80.2	49.8
PA	0.01	0.78	0.01	0.01

a. The river water from the Pickwick reservoir on the Tennessee River (see Table A-19 and Table A-20).

b. Colonies/100 mℓ

c. μg/ℓ

Table 29 also compares fish effluent water quality from a bottom discharge and a surface discharge. The first 65 days of operation (May-July) was tested with a bottom drain for water level control in the fish pond. During this period, surface samples were also taken and the results can be compared in Table 29 for the seasonal averages. Very few differences were found in the seasonal averages (Table 29); however, changes in time were generally observed earlier in the bottom discharge and a somewhat comparable change occurred 7 to 15 days later in the surface discharge. The heat content of the water was conserved by using bottom drainage during the winter. Water temperatures are high during the summer, and therefore, surface drainage helps to reduce the average water temperatures for a better summertime growing environment.

The nitrogen removal rate in the system was approximately 70%. This is lower than predicted by previous tests but is acceptable for water quality standards during this period. The total Kjeldahl nitrogen (TKN) in the effluent water (0.53 mg/ℓ) from the water chestnut polishing was less than that found in incoming river water (0.67 mg/ℓ). However, a much higher percentage (50%) of the effluent nitrogen was total ammonia nitrogen.

Fecal coliforms were much lower than predicted based on previous smaller scale tests. Counts of fecal coliform colonies were less than 10/100 mℓ. This is an improvement over the predicted 400 to 800/100 mℓ. The river water was about 17,000 counts/100 mℓ of fecal coliforms during this same period. This represents a tremendous improvement in the water quality.

The chemical oxygen demand (COD) was nearly triple in the effluent (14 mg/ℓ) compared with the incoming river water (5 mg/ℓ). Tests have indicated that much of this increased COD is in the soluble fraction and not the particulate or insoluble fraction.

The dissolved oxygen (DO) is very low in the discharged effluent and would require reaeration before returning to the "natural" ecosystem. A short interval cascade reaeration system should be planned for the effluent wastewater. Tests have indicated that no more than 30 meters (100 ft) with interval falls 10 cm (6 in.) high would be required for sufficient reaeration.

In summary, the time variation of water quality of the pilot-scale demonstration effluent was predictable during this test period. Water quality was acceptable for most variables tested, and the water quality of other variables can be improved by design changes in the system. Additional testing is needed for estimating water quality for the winter and early spring periods of operation.

Anaerobic Digester Waste Test

The pilot demonstration sampling period took place from January 8, 1980 until April 22, 1980, using anaerobic digester waste as the source of fertilizer. The test conditions were similar to the swine waste demonstration. The digester composite waste effluent (Table 26) was added daily to the ponds (0.013 ha [0.03 Ac]). Simulated waste-heated river water or unheated river water was added continuously to two separate but similar pond and water chestnut demonstration systems. The waste applied from the digester was equivalent to the waste from 16,000 kg of hogs applied to one hectare (14,400 lb/Ac) after being subjected to a digester pretreatment.

Results of this water quality system are not directly comparable to those obtained in the swine waste system during the summer growing period (Table 29). The results shown in Table 30 clearly demonstrate the reduced treatment effectiveness during the winter and early spring period relative to the summer. Nitrogen removal rate is probably the best indicator of this reduced treatment effectiveness when comparing these results. Little nitrogen was removed by the digester, and a high percentage of the nitrogen is total ammonia-N (NH_3 + NH_4^+-N). Because of the low water temperature, the free ammonia (NH_3) concentration was still below the suggested concentration of 0.02 mg/ℓ and approaches a level which is five times lower.

TABLE 30. EFFLUENT WATER QUALITY FROM ANAEROBIC DIGESTER PILOT DEMONSTRATION [JANUARY-APRIL 1980]

Variable	Fish lagoon		Water chestnut		River water
	Heated	Not heated	Heated	Not heated	Influent
	mg/l				
BOD	12	15	14	23	2
COD	39	46	33	40	11
SS	12	14	9	3	3
TS	145	147	137	121	102
FC	10,037	2,400	3,400	2,900	376
TKN	7.8	7.9	8.5	6.7	0.4
NH_3+NH_4^+-N	5.9	5.8	7.3	5.6	0.1
ORGN	1.9	2.4	1.5	1.1	0.1
TOTP	1.3	1.6	1.4	1.3	0.04
TOC	132	98	134	73	116
Ca	48	21	22	21	20
K	6.5	6.5	7.1	6.3	1.5
pH	7.5	7.5	6.8	6.8	7.4
T(°C)	11.3	9.4	9.4	9.4	23.1[a]

a. The temperature reported is the average of the simulated waste-heated river water; unheated influent averaged 10.0°C (50°F) during this period.

The fecal coliform (FC) counts during this period were nearly 10 times the background levels in the river water. This is in contrast to summer results with swine manure where FC counts were < 10/100 mℓ. This level of FC may be partially due to the washout of collected and filterable organic matter through the sand filtration and water chestnut beds. This high FC is partially due to the lower growth rates in the water chestnut beds and fish ponds, and altered microbial activity which is more conducive to the decomposition of organic matter, including the fecal coliform organic matter added to the system. This is also evidenced by the small change that is observed in the organic carbon (TOC) in the effluent streams. The heated effluent had a 25% higher organic carbon content than the unheated effluent. This is not reflected in the BOD, COD, or SS content of the two systems. However, SS in the heated water chestnut effluent was three times higher than the unheated (9 mg/ℓ vs 3 mg/ℓ) and should have been reflected in a corresponding rise in the oxygen demand BOD and/or COD. It is suggested by these results that the higher organic carbon and higher TKN in this test was a result of relatively low oxygen demanding material, was filterable, and produced particle sizes close to those of bacteria.

It is concluded that the heated water did improve the waste treatment effectiveness of this system during this winter/spring season. Plant nutrient uptake is low relative to summer results. However, the annual cycle of nutrient uptake may be different from that of previous tests for other sources of organic waste. A complete study of this system is continuing on an annual basis.

SECTION VIII

ECONOMIC ANALYSIS OF A POWER PLANT AQUAFARM

The system sized in this section is partly based on a sensitivity analysis for a "medium scale" facility. The integrated system did not appear to be economical until a 500- to 1,000-head swine operation was assumed. Therefore, a swine facility size was chosen to give a modest net income potential of approximately $20,000/year. This size finishing facility (2,000-head capacity) is seldom found in the Valley States without a farrowing operation being managed in conjunction with the finishing herd. However, it was assumed that feeder pig production for this facility could be supplied from local markets at an acceptable cost and availability. If the integrated approach of waste reclamation included the sow-farrowing operation, then larger investment cost and larger benefits would be anticipated from the siting of such an operational facility to beneficially use power plant CCW and its waste heat. However, the operational complexity of such a system has not been discussed in this technical report and will not be considered in this economic analysis.

The economic analysis conducted here does not assume a cost benefit to the power plant facility. Implicit in this analysis is a power plant "liability cost" of $1,300/Ac, and this charge is passed on to the user of CCW from the "cooperating" power plant. The question of significant or insignificant amounts of used waste-heat energy relative to total energy available from a power plant, in a hypothetical case, is not a factor in the economic analyses of waste-heat uses. However, at some hypothetical size, a significant amount of waste heat would be used and could represent a significant savings to the power plant in cooling costs. This hypothetical size is not a factor in this economic analysis, but should be considered by utilities to arrive at a fair price for waste-heated water.

The integrated aquafarm system discussed in this analysis would require 650 ℓ/min-ha at a depth of 0.9 m (70 gpm/Ac at 3-ft depth) to maintain a 10-day water retention time for sufficient biological activity to support the aquafarming production system. The Browns Ferry Nuclear Plant requires a 14°C (25°F) ΔT temperature rise of cooling water in the condenser before its return to the Tennessee River. Virtually all of the waste heat would be removed from the CCW used by this integrated system, and the pond area is nearly three times higher than the estimated surface area required for accomplishing just a cooling function. Therefore, it is estimated that 2.1×10^{10} kJ (8×10^{9} Btu/Ac-yr) would be extracted by this system by convectional cooling alone. Evapo-transpirational cooling during the summer months would be considerably larger than that of convection cooling. The convectional cooling capacity of 2.1×10^{10} kJ (8×10^{9} Btu/Ac-yr) compares with 1.3 x 10^{10} kJ (5 x 10^9 Btu/Ac-yr) for greenhouses using wet pad heat exchanger systems or 1.6 times the greenhouse cooling capacity of equivalent area based on research at the Browns Ferry Nuclear Plant. Additionally, the cooling pond cooling capacity is more constant than the greenhouse over an annual basis. The greenhouse approach for using CCW uses the waste heat approximately 5 months of the year, mostly during the winter. However, the land requirement to achieve equal total cooling capacity in the integrated aquafarm system is approximately 7.6 times the land required to remove an equivalent amount of heat with a comparable greenhouse system. But, the ΔT achieved by the greenhouse system would not meet environmental standards for permissible discharge. Normally, a ΔT of 8.3°C (15°F) would be all that a greenhouse would be designed to achieve because of economic considerations. The proposed aquafarm system can remove heat from CCW used for the beneficial purpose. The benefits to the power plant would be primarily a function of how much water was cooled as determined by the size of the aquafarm system.

This economic study was conducted with a computerized investment analysis. The scale of the aquafarm and livestock facility simulated in the analysis consisted of the following:

1. A feeding operation marketing 5,600 finished hogs per year and requiring a barn capacity for 2,000 head,

2. 25 acres of fish ponds producing marketable food fish (tilapia) in conjunction with the hog operation, and

3. 12 acres of Chinese water chestnut beds in conjunction with hog and fish annual production.

The total cost of the project was estimated at about $391,000, the major financial assumptions being given in Table 31. Assumptions relative to prices and quantities of inputs and outputs are found in Table 32.

A projected annual cash flow for each of the first 12 years of operation was generated by subtracting the sum of each year's annualized investment costs and projected variable costs from projected revenues for the year. The effects of anticipated inflation were incorporated into the analysis by means of inflation indices (Table 33). The projected costs of inputs and prices of outputs for each year were generated by multiplying base year costs and prices (Table 32) by the appropriate indices shown in Table 33. For example, the projected cost of electricity per kWh in the fifth year of operation would be $0.034 x 1.943 = $0.066, or 6.6¢/kWh, which equals the base year price of electricity times the inflation index for electricity in year five. The revenue from each hog in year nine would be $95.50 x 2.019 = $192.81.

TABLE 31. MAJOR ASSUMPTIONS OF INVESTMENT ANALYSIS OF A LIVESTOCK-AQUAFARM SYSTEM USING POWER PLANT CONDENSER COOLING WATER

Item	Units	Data
Timeframe of analysis	years	12
Method of depreciation		Straight Line
Investment tax credit rate (where applicable)	%	10
Energy tax credit rate (where applicable)	%	10
Downpayment	%	10
Property tax rate (on book value)	%	0.6
Long-term borrowing rate (> 1 yr)	%	12
Short-term borrowing rate (< 1 yr)	%	14
Years interest paid on investment before operational	years	1/2
Annual waste heat charge	$/acre	1,300

TABLE 32. FIXED COSTS, ANNUAL VARIABLE COSTS, AND REVENUE ITEMS USED IN INVESTMENT ANALYSIS OF A LIVESTOCK-AQUAFARM SYSTEM USING POWER PLANT CONDENSER COOLING WATER

Fixed Costs

Item	Total cost ($)	Useful life (yrs)	Depreciable life (yrs)	Salvage[a] value ($)	Loan period (yrs)	Tax[b] credit	Repair and maintenance (%/yr)[c]
Hog barn	110,000	20	12	11,000	15	I	2
Hog equipment[d]	23,000	9	8	2,000	7	I	3
Fish pond[e]	67,200	20	12	0	15	I,E	2
Fish equipment[f]	13,200	8	7	1,300	6	I,E	8
Chestnut bed[g]	108,000	20	12	0	15	I,E	2
Harvester	12,000	10	8	600	7	I,E	6
Wagon	1,000	15	10	100	6	I	4
Washing/sizing machine	3,500	9	7	350	5	I,E	3
Tractor	12,800	9	7	1,200	5	I,E	6
Truck	18,000	9	7	1,500	5	I	5
Utility building	11,000	15	12	1,000	15	-	2
Mower	1,900	9	7	190	5	I	5
Fuel tank	250	12	8	100	5	I	1
Pickup truck	9,500	8	7	950	5	I	5
Total	391,350						

(continued)

TABLE 32. (continued)

Variable Costs

Item	Unit	Base year cost/unit ($)	Number of units	Base year total cost ($)
Feeder pigs	each	32.00	5,768	184,576
Hog ration	hog	11.60	5,600	64,960
Corn	hog	33.00	5,600	184,800
Other hog costs[h]	hog	5.84	5,600	32,704
Fingerlings	each	0.10	125,000	12,500
Electricity	kWh	.034	205,880	7,000
Labor	h	4.25	5,460	23,205
Diesel fuel	gal	1.10	1,000	1,100
Waste heat	acre	1,300	41	53,300
Chemicals (fish)	misc.	200	-	200
Chestnut bed preparation	acre	75.00	12	900
Chestnut planting	acre	200	12	2,400
Hay baling	acre	100	12	1,200
Management	manager	24,000	1	24,000
Total				592,845

(continued)

TABLE 32. (continued)

Annual Revenues

Item	Unit	Base year price/unit ($)	Number of units	Base year gross revenues
Hogs	each	95.50	5,600	534,800
Fish	lb	0.45	115,000	51,750
Chestnuts	lb	.55	175,000	96,250
Hay	lb	.02	110,000	2,200
Total				685,000

a. Salvage value was used to determine the amount of depreciation to be taken during the declared tax life of the asset. In the event of asset replacement, a trade-in value equal to the salvage value of the asset was assumed.

b. Tax credits include a 10% investment tax credit (I), a 10% energy tax credit (E), or both.

c. Repair and maintenance costs were escalated in subsequent years to reflect aging of equipment and inflation in the costs of replacement parts and labor.

d. Hog equipment includes: feeders, watering nipples, augers, feed storage bin, medicators, pumps, and sprinklers.

e. Fish pond investment includes: earthmoving, drainage structures, gravel and vegetative cover.

f. Fish equipment includes: boat, motor, trailer, relift pump, aeration attachment, oxygen meter, nets, waders, transport tank, scale, thermometers, baskets, chemical applicator, and buckets.

g. Chestnut bed includes: site preparation, sand, pipes, and weir.

h. Other hog costs include: veterinarian and medicine, grinding and mixing of feed, and other livestock material and services.

TABLE 33. INFLATION INDICES UTILIZED IN COMPUTERIZED INVESTMENT ANALYSIS OF A THEORETICAL LIVESTOCK-AQUAFARM SYSTEM USING CCW

Item	Electricity	Diesel fuel	Waste heat	All other costs and revenue items
Year				
1	1.230	1.250	1.020	1.150
2	1.408	1.435	1.056	1.262
3	1.582	1.613	1.104	1.368
4	1.760	1.793	1.163	1.473
5	1.943	1.978	1.233	1.578
6	2.134	2.168	1.315	1.684
7	2.334	2.367	1.409	1.793
8	2.544	2.573	1.518	1.905
9	2.764	2.789	1.642	2.019
10	2.996	3.015	1.783	2.136
11	3.241	3.251	1.945	2.257
12	3.498	3.498	2.129	2.382
12-yr compound rate equivalent	11%	11%	6.5%	7.5%

Table 34 summarizes the principal results of the analysis. The internal rate of return (IRR) on investment in the hypothetical aquafarm system was found to be favorable--about 20%. Since the cutoff for the period of analysis was the end of the twelfth year, an estimated salvage value at that time for the firm's assets was taken into consideration in calculating the IRR.

The cash flow was projected to be negative during the first 2 years of operation and positive thereafter. During the first year of operation, the cash flow was $-33,100. In other words, the investor would have to supply about $33,100 to the project from some other source during the first year of operation. During the second year, a net investment of about $200 would be necessary. In all subsequent years, the enterprise generated positive cash flows.

Total energy and investment tax credits available from the investment were estimated at $59,700. Such tax credits were limited to a 7-year carryover. The projected income tax liabilities of the enterprise during the first seven years of operation were insufficient to permit the capture of any investment or energy tax credits. If the investor had sufficient income tax liabilities from other operations, these tax credits could be applied against those liabilities. If all tax credits could be captured in the first year of operation, the actual cash flow in that year would be

TABLE 34. RESULTS OF INVESTMENT ANALYSIS OF HYPOTHETICAL BIO-RECYCLING ENTERPRISE

Item	Units	Data
Internal rate of return on investment	%	20
Number of years before cash flow is positive	years	2
Sum of energy and investment tax credits available	$	59,700
Sum of energy and investment tax credits unused	$	57,965

$26,600 rather than the $-33,100 reported above, a difference of nearly $60,000. Early use of all available tax credits would tremendously improve prospects for a profitable investment. This suggests that individuals or firms with income tax liabilities from other sources should be the most likely candidates for a livestock aquafarm operation at a power plant.

The results of any investment analysis depend on the assumptions made in carrying out the analysis. A large number of assumptions are implicit in the reported results. The hog budget incorporated into the analysis represented a little-better-than-break-even operation. This was done so that the results of the analysis would primarily reflect returns to the addition of tilapia and water chestnuts to a hog operation. Assumptions were conscientiously made, but in some cases these assumptions were based on little information. For example, at this point in the development stage, relatively little is known about the market potential for either tilapia or Chinese waterchestnuts. Successive computer analyses to gain insight into the sensitivity of changes in prices indicated that a drop of 5¢/lb in the assumed prices of tilapia and Chinese water chestnuts from 45¢ and 55¢, respectively, to 40¢ and 50¢ (all other assumptions unaltered) would turn the venture into a losing proposition. Market trials could lead to a different range of price expectations for each of these products--either higher or lower. Additionally, economic success or failure of the waste-heat user is very sensitive to the charges demanded for the use of waste heat. Recognition of mutual benefit of waste heat could result in minimal charges for efficient use of waste-heated water.

SECTION IX

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SECTION X

Appendix

TABLE A-1. PRODUCTION TEST: FISH EFFLUENT WATER QUALITY [MAY-DECEMBER 1979]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	72	18.8	9.11	1.00	58.0	48
COD	42	79.7	40.9	11.0	160	51
SS	64	53.3	32.5	5.00	150	61
TS	75	581	107	350	820	18
STS[a]	21	0.61	0.99	0.20	4.00	161
TKN	68	3.03	1.28	1.20	7.70	42
NH_3	72	0.44	0.78	0.02	4.50	176
ORGN	68	2.57	1.17	0.13	7.00	45
NO	72	0.25	0.35	0.01	1.10	137
TOTP	68	1.30	0.72	0.27	4.00	55
TOC	15	38.0	12.5	25.0	70.0	33
TOTC	15	49.5	11.9	38.0	83.0	24
TC[b]	36	300086	550804	100	2000000	183
FC[b]	36	5890	14158	10.0	76000	240
Ca	42	47.1	16.1	22.0	92.0	34
Mg	42	4.5	0.65	3.6	6.6	14
Na	42	119	24.4	59.0	160	20
K	42	8.35	1.97	5.20	12.0	23
Fe[c]	42	267	456	50.0	3000	171
Cu[c]	39	14.1	8.8	10.0	50.0	62
Zn[c]	42	119	121	10.0	670	101
Pb[c]	27	10.0	0.0	10.0	10.0	0
As[c]	75	2.10	0.53	2.00	6.00	25
Mn[c]	9	51	31.7	20	130	62
DO	66	13.0	5.62	2.70	26.1	42
HARD	21	142	11.5	120	170	8
pH	36	8.51	1.01	6.41	9.94	11
T(°C)	42	26.4	3.33	16.0	31.0	12
TA	36	170	234	69.0	980	137
PA	36	12.3	15.3	0.01	47.0	124
CB	43	968.1	105.3	600.0	1200	10
Algae[d]	33	991242.0	817802.0	72000.0	3726000.0	82

a. mℓ/ℓ

b. Colonies/100 mℓ

c. μg/ℓ

d. Cells/mℓ

n = number of observations

TABLE A-2. PRODUCTION TEST: CHESTNUT EFFLUENT WATER QUALITY [MAY-DECEMBER 1979]
FLOW RATE = 57 ℓ/m^2-day

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	72	3.8	4.11	1.00	21.0	108
COD	42	23.5	22.3	5.00	130	94
SS	74	8.9	14.4	1.00	91.0	160
TS	75	514	98.4	320	760	19
TKN	67	0.77	0.59	0.30	4.30	76
NH_3	72	0.16	0.25	0.01	1.10	151
ORGN	67	0.59	0.52	0.12	4.10	88
NO	72	0.06	0.24	0.01	2.00	372
TOTP	67	0.32	0.28	0.04	1.50	88
TOC	15	17.8	10.6	4.80	36.0	59
TOTC	15	34.0	11.3	9.00	51.0	33
TC[a]	36	214038	470907	100.0	2000000	220
FC[a]	36	750	1602	10.0	9000	213
Ca	42	48.8	17.4	21.0	91.0	35
Mg	42	4.27	0.95	1.20	5.90	22
Na	42	115	23.3	67.0	160	20
K	42	6.66	3.11	2.20	21.0	46
Fe[b]	42	1537	1553	130	8000	101
Cu[b]	41	16.5	31.1	10.0	210	188
Zn[b]	42	43.3	130	10.0	850	300
As[b]	75	26.5	1.17	2.00	8.00	44
Mn[b]	9	50.0	20.6	30.0	100	41
DOB	50	9.34	4.55	2.50	19.3	48
DOS	51	1.26	2.22	0.20	9.80	175
HARD	21	134	23.2	98.0	184	17
pH	36	6.82	0.42	6.31	8.81	6
TB(°C)	60	22.7	5.19	11.0	29.0	22
TA	36	103	16.5	65.0	143	16
PA	36	0.17	0.99	0.01	6.00	565
CB	42	921	127	680	1210	13
CP	43	910	145	650	1250	15
Algae[c]	32	492812	583866	13000	2243000	118
TP(°C)	63	22.6	4.65	12.0	29.0	20

a. Colonies/100 mℓ

b. μg/ℓ

c. Cells/mℓ

TABLE A-3. PRODUCTION TEST: CHESTNUT EFFLUENT WATER QUALITY [MAY-DECEMBER 1979]
FLOW RATE = 96 ℓ/m^2-day

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		------------------	---------mg/ℓ---------	------------------	------------------	
BOD	72	4.66	4.17	0.10	18.0	89
COD	42	25.2	22.7	4.00	120	89
SS	75	8.37	13.2	1.00	92.0	158
TS	75	544	172	340	1800	31
TKN	67	1.03	0.79	0.36	4.30	76
NH_3	72	0.40	0.61	0.01	3.30	149
ORGN	67	0.76	1.01	0.12	7.40	132
NO	72	0.08	0.18	0.01	1.20	215
TOTP	67	0.44	0.39	0.03	1.80	89
TOC	15	17.8	10.0	6.20	41.0	56
TOTC	15	32.9	10.6	9.00	50.0	32
TC^a	36	291522	577998	600	2000000	198
FC^a	36	650	1207	10.0	7000	185
Ca	42	49.6	17.7	21.0	89.0	35
Mg	42	4.37	0.96	1.00	5.80	21
Na	42	117	30.3	4.80	160	25
K	42	7.23	5.22	1.50	31.0	72
Fe^b	42	1360	1034	190	3900	76
Cu^b	41	11.7	3.80	10.0	20.0	32
Zn^b	42	19.2	17.5	10.0	90.0	91
As^b	75	2.56	1.00	2.00	7.00	39
Mn^b	9	45.5	11.3	30.0	70.0	24
DOB	51	8.25	5.12	1.20	20.4	62
DOS	49	1.69	3.00	0.10	12.0	177
HARD	21	141	20.8	102	188	14
pH	36	6.81	0.45	6.23	8.86	6
TB(°C)	60	22.8	5.13	11.0	29.0	22
TA	36	107	16.8	67.0	136	15
CB	43	937	114	710	1210	12
CP	43	923	131	710	1250	14
Algae^c	32	550000	716264	13000	2557000	130
TP(°C)	63	22.6	4.66	12.0	29.0	20

a. Colonies/100 mℓ

b. µg/ℓ

c. Cells/mℓ

TABLE A-4. PRODUCTION TEST: CHESTNUT EFFLUENT WATER QUALITY [MAY-DECEMBER 1979]
FLOW RATE = 151 ℓ/m^2-day

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	72	5.08	4.34	1.00	18.0	85
COD	42	25.6	25.5	3.00	140	99
SS	75	11.9	24.3	1.00	160	204
TS	75	532	92.4	350	790	17
TKN	68	1.13	0.98	0.34	4.70	86
NH_3	72	0.41	0.64	0.01	3.70	154
ORGN	68	0.72	0.64	0.22	3.40	88
NO	72	0.16	0.79	0.01	6.70	486
TOTP	67	0.61	0.92	0.05	7.00	150
TOC	15	19.3	0.98	7.20	44.0	51
TOTC	15	37.0	10.0	24.0	58.0	27
TC[a]	36	147177	265764	200	1160000	180
FC[a]	36	450	474	10.0	1000	105
Ca	42	51.6	18.5	20.0	93.0	35
Mg	42	4.44	0.85	1.40	5.90	19
Na	42	120	30.8	4.80	170	25
K	42	7.45	5.76	1.60	30.0	77
Fe[b]	42	1383	1646	90.0	7500	118
Cu[b]	41	13.1	6.09	10.0	30.0	46
Zn[b]	42	33.3	60.1	10.0	350	180
As[b]	75	2.34	0.77	2.00	6.00	33
Mn[b]	9	49.7	10.0	40.0	70.0	20
DOB	50	7.83	5.22	1.40	22.8	66
DOS	51	1.74	2.95	0.10	11.0	169
HARD	21	140	18.1	105	176	12
pH	36	6.87	0.64	6.05	9.22	9
TB(°C)	60	22.8	5.12	11.0	29.0	22
TA	36	107	15.3	71.0	138	14
PA	36	0.39	2.33	0.01	14.0	584
CB	43	939	113	710	1210	12
CP	43	926	123	710	1220	13
Algae[c]	33	615696	983649	21000	5324000	159
TP(°C)	63	22.6	4.68	12.0	29.0	20

a. Colonies/100 mℓ

b. μg/ℓ

c. Cells/mℓ

TABLE A-5. PRODUCTION TEST. FISH EFFLUENT WATER QUALITY (JANUARY-APRIL 1980)

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	21	26.2	11.4	12.0	53.0	43
COD	21	61.7	21.4	26.0	100	34
SS	21	30.0	32.5	4.00	150	108
TS	21	386	66.0	280	480	17
FC[a]	21	2461	4526	100	20000	183
TKN	21	3.29	0.98	1.70	5.50	29
NH_3	21	0.73	0.72	0.03	2.30	98
ORGN	21	2.56	0.77	1.50	4.00	30
TOTP	21	1.31	0.62	0.16	2.80	47
TOC	21	171	124	13.2	500	72
Ca	20	39.1	5.76	30.0	48.0	14
K	21	7.26	0.80	5.90	8.30	11
pH	15	8.36	0.55	7.32	8.91	6
T(°C)	24	8.62	4.92	3.00	18.0	57

[a] Colonies/mℓ

TABLE A-6. PRODUCTION TEST: POST HARVEST EFFLUENT WATER QUALITY (JANUARY-APRIL 1980)
FLOW RATE = 57 ℓ/m^2-day

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	21	13.2	7.03	3.00	28.0	53
COD	21	47.1	31.4	11.0	160	66
SS	21	13.3	23.0	1.00	110	172
TS	21	359	60.4	260	460	16
FC[a]	21	561	885	100	4000	157
TKN	21	2.70	0.79	1.40	4.20	29
NH_3	21	1.28	0.63	0.05	2.60	49
ORGN	21	1.37	0.64	0.13	2.60	47
TOTP	21	1.08	0.53	0.41	2.9	48
TOC	21	122	204	7.70	900	166
Ca	21	40	6.56	28.0	50.0	16
K	21	7.74	1.22	5.00	9.20	15
pH	15	7.54	0.46	6.90	8.91	6
TB(°C)	24	8.62	4.92	3.00	18.0	57

[a] Colonies/mℓ

TABLE A-7. PRODUCTION TEST: POST HARVEST EFFLUENT WATER QUALITY [JANUARY-APRIL 1980]
FLOW RATE = 96 ℓ/m^2-day

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	21	16.5	12.8	5.00	60.0	77
COD	21	53.2	3.9	18.0	150	61
SS	21	10.4	6.05	1.00	22.0	58
TS	21	379	88.2	250	590	23
FC[a]	21	433	528	100	2000	121
TKN	21	3.42	1.20	1.70	6.80	35
NH_3	21	1.83	1.04	0.53	4.90	57
ORGN	21	1.59	0.52	0.59	2.70	32
TOTP	21	1.57	1.04	0.48	5.40	66
TOC	21	95.7	134	11.0	500	140
Ca	21	42.9	9.15	29.0	62.0	21
K	21	8.21	1.11	5.80	9.80	13
pH	16	9.75	9.13	6.86	44.0	93
T(°C)	24	8.62	4.92	3.00	18.0	57

a. Colonies/mℓ

TABLE A-8. PRODUCTION TEST: POST HARVEST EFFLUENT WATER QUALITY [JANUARY-APRIL 1980]
FLOW RATE = 151 ℓ/m^2-day

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	21	19.7	10.3	8.00	46.0	52
COD	21	59.7	35.5	21.0	170.0	59
SS	21	13.0	11.9	1.00	52.0	91
TS	21	362	74.1	190	450	20
FC[a]	21	1062	1869	100	7900	175
TKN	21	3.53	0.96	1.70	5.90	27
NH_3	21	1.92	1.05	0.77	4.30	54
ORGN	21	1.75	0.43	0.91	2.70	24
TOTP	21	1.41	0.72	0.16	3.30	51
TOC	21	113	127	11.0	400	112
Ca	21	41.1	7.15	32.0	58.0	17
K	21	8.01	1.02	6.60	10.0	12
pH	15	7.27	0.22	6.79	7.59	3
TB(°C)	24	8.62	4.92	3.00	18.0	57

a: Colonies/100 mℓ

TABLE A-9. PILOT DEMONSTRATION: FISH LAGOON EFFLUENT WATER QUALITY: BOTTOM DISCHARGE [MAY-JULY 1979]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	9	12.6	5.48	1.80	20.0	43
COD	6	46.0	38.1	4.00	98.0	83
SS	9	56.2	43.2	2.00	150	76
TS	9	357	184	160	710	51
TKN	9	3.43	1.92	0.12	6.80	56
NH_3	9	1.75	1.07	0.02	3.50	61
ORGN	9	1.66	0.96	0.10	3.30	57
NO	9	0.27	0.61	0.04	1.90	226
TOTP	8	2.02	2.44	0.01	7.70	120
TOC	5	28.6	15.2	4.20	44.0	53
TOTC	5	39.6	21.1	4.20	58.0	53
TC^a	5	52500	82802	2500.0	200000	157
FC^a	5	1044	998	10.00	2000	95
Ca	5	25.6	7.63	15.0	35.0	29
Mg	5	4.26	0.52	3.60	4.80	12
Na	5	61.3	59.9	8.70	160	97
K	5	6.38	1.82	4.00	8.80	28
Fe^b	5	1356	1487	50.00	3900	109
Cu^b	4	17.5	9.57	10.0	30.0	54
Zn^b	5	76.0	65.4	20.0	180	86
Pb^b	9	10.0	0.00	10.0	10.0	0
As^b	9	4.22	2.43	2.00	10.0	57
HARD	2	81.0	15.5	70.0	92.0	19
pH	4	7.28	0.16	7.08	7.44	2
T(°C)	7	27.8	2.19	25.0	31.0	7
TA	4	77.0	7.87	69.0	86.0	10
PA	5	0.01	0.00	0.01	0.01	0
C^c	6	311	90.4	250	480	29
$Algae^d$	4	736750	192444	607000	1023000	26

a. Colonies/100 mℓ

b. µg/ℓ

c. µhmos/cm

d. Cells/mℓ

TABLE A-10. PILOT DEMONSTRATION: FISH LAGOON EFFLUENT WATER QUALITY: SURFACE DISCHARGE [MAY-OCTOBER 1979]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		----------	----------	-mg/ℓ-	----------	
BOD	18	14.6	9.76	2.40	44.0	66
COD	10	55.6	27.2	28.0	110	49
SS	19	35.5	25.1	6.00	89.0	70
TS	19	260	119	150	530	45
TKN	19	3.17	0.79	2.00	5.30	25
NH_3	19	1.53	1.04	0.21	4.60	68
ORGN	19	1.65	0.73	0.42	3.00	44
NO	19	0.20	0.22	0.03	0.85	109
TOTP	18	0.79	0.30	0.38	1.40	38
TOC	5	29.6	8.73	21.0	42.0	29
TOTC	5	42.8	9.65	29.0	53.0	22
TC^a	9	336911	651205	8900.00	2000000	193
FC^a	9	17114	35123	10.000	100000	205
Ca	10	27.1	18.6	15.0	79.0	68
Mg	10	4.53	0.57	3.80	5.70	12
Na	10	33.7	34.0	7.70	110	101
K	10	6.73	2.66	4.60	14.0	39
Fe^b	10	1122	418.5	490.0	1800	37
Cu^b	9	14.4	10.1	10.0	40.0	70
Zn^b	10	69.0	107	10.0	370	155
Pb^b	9	10.0	0.00	10.0	10.0	0
As^b	19	4.21	2.20	2.00	10.0	52
Mn^b	3	220	26.4	200	250	12
DO	14	3.27	2.37	0.40	8.00	72
HARD	5	85.6	29.2	66.0	137	34
pH	8	7.51	0.67	6.80	8.82	8
T(°C)	15	28.0	4.33	16.0	32.0	15
TA	8	74.5	15.2	65.0	106	20
PA	9	0.78	2.33	0.01	7.00	296
C	13	953	1379	220	4500	144
$Algae^c$	6	731666	352783	313000	1329000	48

a. Colonies/100 mℓ

b. μg/ℓ

c. Cells/mℓ

TABLE A-11. PILOT DEMONSTRATION/ANAEROBIC DIGESTER TEST: FISH LAGOON EFFLUENT CHARACTERISTICS RECEIVING UNHEATED RIVER WATER [JANUARY-APRIL 22, 1980]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	8	15.2	5.76	8.40	24.0	37
COD	8	45.6	19.6	16.0	76.0	43
SS	8	13.6	7.94	2.00	24.0	58
TS	8	147	15.8	120	170	10
FC[a]	8	2375	2890	100	8200	121
TKN	8	7.88	1.81	5.40	11.0	22
NH_3	8	5.52	1.43	3.30	7.90	25
ORGN	8	2.36	0.45	1.60	3.10	19
TOTP	8	1.57	0.31	1.30	2.30	20
TOC	8	98.5	115	11.0	300	117
Ca	8	20.8	2.41	16.0	23.0	11
K	8	6.45	1.24	4.90	8.20	19
pH	5	7.51	0.43	6.99	8.20	5
T(°C)	8	9.37	4.59	4.00	18.0	49

[a] Colonies/100 mℓ

TABLE A-12. PILOT DEMONSTRATION/ANAEROBIC DIGESTER TEST: FISH LAGOON EFFLUENT CHARACTERISTICS RECEIVING SIMULATED WASTE-HEATED CONDENSER COOLING WATER FROM THE BROWNS FERRY NUCLEAR PLANT [JANUARY-APRIL 22, 1980]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	8	12.2	5.73	6.00	23.0	46
COD	8	38.7	22.1	21.0	92.0	57
SS	8	12.1	6.55	3.00	22.0	54
TS	8	145	32.9	110	210	22
FC[a]	8	10037	14020	100	36000	139
TKN	8	7.76	1.77	5.50	10.0	22
NH_3	8	5.88	1.97	3.30	8.60	33
ORGN	8	1.90	0.60	1.30	2.80	31
TOTP	8	1.31	0.25	0.90	1.60	19
TOC	8	132	141	13.2	400	106
Ca	8	47.7	77.7	16.0	240	162
K	8	6.51	1.31	4.40	8.50	20
pH	5	7.46	0.46	6.85	8.09	6
TB(°C)	8	11.3	4.10	6.00	19.0	36

a. Colonies/100 mℓ

TABLE A-13. PILOT DEMONSTRATION/ANAEROBIC DIGESTER TEST PLANT POLISHING EFFLUENT DURING WINTER-SPRING [JANUARY-APRIL 1980] RECEIVING FISH WASTE WATER FROM THE UNHEATED RIVER WATER TEST

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	8	22.7	30.0	5.60	95.0	131
COD	8	39.8	19.4	22.0	84.0	48
SS	8	3.25	1.75	1.00	6.00	53
TS	8	121	21.0	90.0	150	17
FC[a]	8	2937	6907	100.0	20000	235
TKN	8	6.68	1.37	4.40	8.10	20
NH_3	8	5.57	1.17	3.60	6.70	21
ORGN	8	1.14	0.46	0.66	2.10	40
TOTP	8	1.27	0.26	0.77	1.60	21
TOC	8	72.8	83.6	14.3	200	114
Ca	8	21.2	2.05	17.0	24.0	9
K	8	6.31	0.87	5.00	7.30	13
pH	2	6.84	0.24	6.67	7.01	3

a. Colonies/100 mℓ

TABLE A-14. PILOT DEMONSTRATION/ANAEROBIC DIGESTER TEST: PLANT POLISHING EFFLUENT DURING WINTER-SPRING [JANUARY-APRIL 1980] RECEIVING FISH WASTE WATER FROM THE HEATED RIVER WATER TEST

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	8	14.2	11.0	4.40	35.0	77
COD	8	32.7	14.4	20.0	60.0	44
SS	8	8.75	6.75	2.00	18.0	77
TS	8	137	18.3	110	160	13
FC[a]	8	3437	6809	100.0	20000	198
TKN	8	8.5	1.4	6.9	11.0	17
$NH_3+NH_4^+$	8	7.32	1.45	5.00	10.0	19
ORGN	8	1.5	0.8	0.74	3.0	55
TOTP	8	1.41	0.30	0.99	1.90	21
TOC	8	134	206	12.1	600	153
Ca	8	22.1	1.88	18.0	24.0	8
K	8	7.08	1.13	5.30	9.00	15
pH	2	6.77	0.01	6.77	6.78	0

a. Colonies/100 mℓ

TABLE A-15. SWINE MANURE USED IN PILOT DEMONSTRATION AND PRODUCTION TEST [MAY-DECEMBER 1979]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	26	1953	939	920	4200	48
COD	15	4549	3096	1200	13000	68
SS	27	2567	1098	1200	4750	42
TS	27	4044	1057	2500	5800	26
STS[a]	27	37.4	17.5	0.40	70.0	46
TVS	27	2618	982.9	780.0	4750	37
TKN	24	355	187	170	1070	52
NH_3	26	233	132	28.0	730	59
ORGN	24	133	120	3.00	442	90
NO	26	0.20	0.41	0.01	1.60	205
TOTP	24	124	90.5	28.0	470	72
TOC	16	2503	1239	1000	6500	49
TOTC	16	3618	1458	1800	7250	40
TC[b]	13	7000000	8272771	200000	20000000	118
FC[b]	13	645747	1027927	220	3500000	159
Ca	15	182	63.6	80.0	320	34
Mg	15	46.1	14.3	9.80	71.0	31
Na	15	161	63.0	87.0	310	39
K	15	198	73.4	95.0	380	36
Fe[c]	15	6775	3387	530.0	15000	49
Cu[c]	14	274	124	20.0	520	45
Zn[c]	15	4330	1489	1500	6800	34
Pb[c]	20	34.7	36.8	10.0	150	106
As[c]	27	8.25	5.30	2.00	19.0	64
Se[c]	15	4.44	5.90	1.00	24.0	132
Mn	3	2800	888	2100	3800	31

a. mℓ/ℓ

b. Colonies/100 mℓ

c. μg/ℓ

TABLE A-16. SWINE MANURE CHARACTERISTICS

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		--------	--------	mg/ℓ	--------	
			[JANUARY-APRIL 1980]			
BOD	9	1777	471	1000	2600	26
COD	9	4366	4047	2100	15000	92
SS	9	3411	1913	2100	7800	56
TS	9	4477	1745	3600	9000	38
TVS	9	2297	998.2	630.0	3500	43
STS[a]	9	33.3	10.2	18.0	50.0	30
FC[b]	8	419500	646517	50000	2000000	154
TKN	9	367	98.0	192	510	26
NH_3	9	182	88.0	2.80	265	48
ORGN	9	185	85.5	69.0	320	46
TOTP	9	124	41.0	70.0	185	33
TOC	9	2066	981.0	1100	4400	47
Ca	9	290	343	67.0	1200	118
K	8	168	61.2	100	300	36
			[OCTOBER 1979 - APRIL 1980]			
pH	9	8.18	0.26	7.91	8.58	3
TA	9	862	216	550	1163	25
Total acid	9	44.4	48.5	0.00	120	109
Volatile acid	9	152	65.2	81.0	274	42

a. mℓ/ℓ

b. Colonies/100 mℓ

TABLE A-17. GROUND WATER SOURCE: WATER QUALITY [MAY-DECEMBER 1979]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
BOD	14	6.92	10.5	1.00	32.0	152
COD	11	5.00	2.28	2.00	9.00	45
SS	13	2.38	1.44	1.00	6.00	60
TS	13	453	172	110	630	38
TKN	12	0.96	2.36	0.06	8.40	245
NH_3	12	0.03	0.02	0.01	0.07	79
ORGN	11	0.89	2.45	0.03	8.30	273
NO	12	1.81	1.20	0.01	5.00	66
TOTP	12	0.25	0.82	0.01	2.86	327
TOC	4	22.2	33.9	3.00	73.0	152
TOTC	3	25.0	1.00	24.0	26.0	4
TC[a]	10	82280	148229	1000	450000	180
FC[a]	10	1733	3350	10.00	11000	193
Ca	12	49.5	21.2	22.0	95.0	43
Mg	12	3.85	0.47	3.20	4.90	12
Na	12	109	54.3	4.60	160	49
K	12	5.46	1.79	1.40	8.90	32
Fe[b]	12	122	93.6	50.0	400	76
Cu[b]	11	11.8	4.04	10.0	20.0	34
Zn[b]	12	149	112	30.0	370	75
Pb[b]	4	10.0	0.00	10.0	10.0	0
As[b]	11	2.00	0.00	2.00	2.00	0
Mn[b]	3	13.3	5.77	10.0	20.0	43
DO	4	5.92	3.19	3.40	10.6	53
HARD	7	135	12.9	116	155	9
pH	12	7.21	0.38	6.74	8.19	5
T(°C)	3	20.3	1.15	19.0	21.0	5
TA	12	88.7	8.31	77.0	107	9

a. Colonies/100 mℓ

b. μg/ℓ

TABLE A-18. GROUND WATER SOURCE WATER QUALITY

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
[JANUARY-APRIL 1980]						
BOD	7	1.45	1.12	1.00	4.00	77
COD	7	7.00	5.83	4.00	20.0	83
SS	7	1.57	1.13	1.00	4.00	72
TS	7	380	101	180	520	26
FC[a]	7	357	439	100	1000	122
TKN	7	0.09	0.05	0.03	0.17	55
$NH_3+NH_4^+$	7	0.02	0.02	0.01	0.09	99
ORGN	7	0.07	0.04	0.01	0.13	67
TOTP	7	0.01	0.00	0.01	0.02	33
TOC	7	61.3	94.6	5.50	200	154
Ca	7	39.4	9.12	25.0	49.0	23
K	7	4.92	1.61	2.30	6.30	32
pH	2	7.01	0.13	6.92	7.11	1
T(°C)	8	8.50	5.23	3.00	18.0	61

a. Colonies/100 mℓ

TABLE A-19. RIVER WATER SOURCE: WATER QUALITY [MAY-DECEMBER 1979]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	12	5.36	13.1	1.00	47.0	244
COD	10	5.10	2.55	2.00	9.00	50
SS	11	3.00	4.42	1.00	16.0	147
TS	11	196	167	100	580	85
TKN	11	0.67	1.43	0.16	5.00	211
NH_3	12	0.05	0.02	0.02	0.11	51
ORGN	11	0.62	1.45	0.09	5.00	233
NO	11	0.31	0.09	0.14	0.49	30
TOTP	12	0.19	0.54	0.01	1.92	286
TOC	4	19.1	26.6	4.20	59.0	139
TOTC	3	20.3	5.13	16.0	26.0	25
TC[a]	9	101611	270036	600.000	820000	265
FC[a]	9	4135	9779	10.00	30000	236
Ca	10	20.8	7.49	16.0	41.0	36
Mg	10	3.79	0.43	3.10	4.60	11
Na	10	24.9	33.4	4.50	87.0	133
K	10	1.70	0.82	1.20	4.00	48
Fe[b]	10	181	108	50.0	420	60
Cu[b]	9	12.2	4.40	10.0	20.0	36
Zn[b]	10	29.0	28.0	10.0	90.0	96
Pb[b]	5	10.0	0.00	10.0	10.0	0
As[b]	11	2.00	0.00	2.00	2.00	0
Mn[b]	2	30.0	28.2	10.0	50.0	94
DO	4	8.07	2.68	4.50	10.6	33
HARD	6	66.0	4.89	60.0	70.0	7
pH	9	7.57	0.22	7.10	7.91	3
T($^{\circ}$C)	2	18.5	3.53	16.0	21.0	19
TA	9	49.8	4.22	46.0	57.0	8
PA	11	0.01	0.00	0.01	0.01	0

a. Colonies/100 mℓ

b. µg/ℓ

TABLE A-20. RIVER WATER SUPPLY CHARACTERISTICS [JANUARY-APRIL 1980]

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
BOD	8	2.15	1.68	1.00	6.00	78
COD	8	10.5	8.22	3.00	29.0	78
SS	8	2.87	3.48	1.00	9.00	121
TS	8	102	16.6	70.0	120	16
FC[a]	8	376	425	10.0	1000	113
TKN	8	0.35	0.50	0.14	1.60	144
NH_3	8	0.06	0.02	0.03	0.11	35
ORGN	8	0.10	0.04	0.03	0.16	45
TOTP	8	0.04	0.01	0.04	0.08	27
TOC	8	116	177	5.50	500	152
Ca	8	19.8	1.55	17.0	21.0	7
K	8	1.46	0.11	1.30	1.60	8
pH	2	7.42	0.36	7.16	7.68	4
T(^{o}C)	8	23.1	2.23	21.0	28.0	9

a. Colonies/mℓ

TABLE A-21. SUPERNATANT CHARACTERISTICS OF SETTLED SWINE MANURE

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
[JANUARY-APRIL 1980]						
BOD	8	817	197	480	1100	24
COD	7	3827	4824	12.00	13000	126
SS	7	510	175	340	770	34
TS	7	1500	270.8	1200	1900	18
TVS	7	775	127	610	1000	16
STS[a]	7	1.21	2.11	0.20	6.00	174
FC[b]	6	742000	977144	1000	2000000	131
TKN	7	282	81.6	176	430	28
NH_3	7	165	51.6	115	250	31
ORGN	7	116	95.3	10.0	285	81
TOTP	7	35.5	11.6	23.0	50.0	32
TOC	7	1900	981.4	600.0	3800	51
Ca	7	78.5	17.0	48.0	98.0	21
K	7	128	21.1	110	160	16
[OCTOBER 1979 - APRIL 1980]						
pH	13	7.97	0.82	5.66	8.48	10
TA	13	674	269	50.0	1000	39
Total acid	13	33.4	56.5	0.00	160	168
Volatile acid	13	159	96.1	81.0	451	60

a. mℓ/ℓ

b. Colonies/100 mℓ

TABLE A-22. SETTLED SOLIDS CHARACTERISTICS OF SWINE MANURE USED TO LOAD AN ANAEROBIC DIGESTER

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
[JANUARY-APRIL 1980]						
BOD	7	11485	4088.7	7000.0	17000	35
COD	7	25164	16629	150.00	51000	66
SS	7	27871	30052	7200.0	83000	107
TS	7	45571	22329	1900.0	81000	49
TVS	7	36871	21970	4100.0	69000	59
STS[a]	7	582	263	360	990	45
FC[b]	6	733666	984926	1000.00	2000000	134
TKN	7	1572	682.8	740.0	2620	43
NH_3	7	382	186	100	610	48
ORGN	7	1194	577.0	530.0	2010	48
TOTP	7	1855	1040	870.0	4000	56
TOC	7	5371	3372	1900	12300	62
Ca	7	1631	776.7	670.0	2800	47
K	7	242	72.0	170	350	29
[OCTOBER 1979 - APRIL 1980]						
pH	13	6.73	0.46	6.02	7.58	6
TA	13	1656	731	850	3000	44
Total acid	13	682	576	100	2230	84
Volatile acid	13	535	392	139	1440	73

a. mℓ/ℓ

b. Colonies/100 mℓ

TABLE A-23. DIGESTER EFFLUENT CHARACTERISTICS

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ				
[JANUARY-APRIL 1980]						
BOD	8	6312	2596	4200	12000	41
COD	8	20500	6000.0	11000	29000	29
SS	8	32250	20026	11000	76000	62
TS	8	35000	11807	19000	59000	33
TVS	8	22850	12183	4900.0	44000	53
STS[a]	8	657	246	380	950	37
FC[b]	7	438714	693494	1000.00	2000000	158
TKN	8	1728	428.8	960.0	2200	24
NH_3	8	701	199	440	1000	28
ORGN	8	1020	422.2	350.0	1700	41
TOTP	8	1783	543.5	1300	3000	30
TOC	8	5300	1190	3600	7100	22
Ca	8	1535	763	190	2500	49
K	8	233	26.6	180	270	11
[OCTOBER 1979 - APRIL 1980]						
pH	13	7.21	0.32	6.70	7.75	4
TA	13	4405	1260	2225	6900	28
Total acid	13	696	290	330	1340	41
Volatile acid	13	1215	1108	56.0	3206	91

a. mℓ/ℓ

b. Colonies/100 mℓ

TABLE A-24. COMPOSITE EFFLUENT (DIGESTER EFFLUENT + SUPERNATANT)

Variable	n	Mean	Standard deviation	Minimum value	Maximum value	C.V. %
		mg/ℓ	mg/ℓ	mg/ℓ	mg/ℓ	
[JANUARY-APRIL 1980]						
BOD	7	1002	250.7	700.0	1400	25
COD	7	3754	4604	880.0	14000	122
SS	7	2137	2342	500	7100	109
TS	7	2100	420.3	1400	2600	20
TVS	7	1210	242.9	770.0	1500	20
STS[a]	7	15.1	12.2	2.00	40.0	81
FC[b]	6	764333	962496	1000.00	2000000	125
TKN	7	341	106	230	520	31
NH_3	7	185	49.8	110	235	26
ORGN	7	156	118	55.0	365	75
TOTP	7	76.7	26.5	50.0	115	34
TOC	7	1914	1172	900.0	4400	61
Ca	7	115	20.3	81.0	140	17
K	7	128	15.7	110	150	12
[OCTOBER-APRIL 1980]						
pH	7	7.84	0.67	6.50	8.46	8
TA	7	760	240	350	1000	31
Total acid	7	65.1	79.2	0.00	215	121
Volatile acid	7	133	36.5	107	201	27

a. mℓ/ℓ

b. Colonies/100 mℓ

TABLE A-25. METAL SCAN OF PRODUCTION TEST EFFLUENT SWINE MANURE AND PILOT DEMONSTRATION EFFLUENT [MAY-JUNE 1979]

	n	Al	B	Ba	Be	Cd	Co	Cr	Mn	Mo	Ni	Sb	Si	Ti	V
		mg/ℓ													
Fish tank	6	0.7	0.03	0.04	<0.01	<0.01	<0.02	<0.03	0.03	<0.05	<0.10	<0.10	3.97	<0.01	<0.01
Bed FR=57	6	.09	.04	.03	<.01	<.01	<.02	<.03	.03	<.05	<.10	<.10	3.27	<.01	<.01
Bed FR=96	6	.07	.04	.03	<.01	<.01	<.02	<.03	.04	<.05	<.10	<.10	3.48	<.01	<.01
Bed FR=151	6	.10	.03	.03	<.01	<.01	<.02	<.03	.04	<.05	<.10	<.10	3.32	<.01	<.01
Manure	2	1.5	.23	.24	<.01	<.01	.06	.04	1.6	<.05	<.10	<.10	1.34	<.01	.02
Pilot demonstration	3	0.31	.04	.07	<.01	<.01	.03	.03	0.25	<.05	<.10	<.10	3.50	.01	<.01

TABLE A-26. A LISTING OF SAMPLE DATES FOR WATER QUALITY MEASUREMENTS DURING THE PRODUCTION TEST PERIODS AND THE TESTING PERIOD DURING THE SWINE WASTE PILOT DEMONSTRATION AS GRAPHICALLY ILLUSTRATED IN FIGURE 15

Spring/Summer/Fall (Preharvest)		Winter/Spring (Postharvest)	
Day	Date	Day	Date
12	5-30-79	235	1-08-80
18	6-05-79	242	1-15-80
25	6-12-80	256	1-29-80
32	6-19-79	270	2-12-80
39	6-26-79	284	2-26-80
48	7-05-79	298	3-11-80
54	7-11-79	312	3-25-80
60	7-17-79	326	4-08-80
67	7-24-79	340	4-22-80
74	7-31-79		
82	8-08-79		
88	8-14-79		
95	8-21-79		
102	8-28-79		
110	9-05-79		
116	9-11-79		
123	9-18-79		
130	9-25-79		
138	10-03-79		
145	10-10-79		
151	10-16-79		
158	10-23-79		
165	10-30-79		
172	11-06-79		
193	11-27-79		
200	12-04-79		
206	12-10-79		